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# THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

Edited by

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

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Ryerson Physical Laboratory of the University of Chicago

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## JUNE 1931

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† Died May 9, 1931.

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# VELOCITY-CURVE AND SPECTRAL VARIATIONS OF 27 CANIS MAJORIS

By OTTO STRUVE

ABSTRACT

The *velocity-curve of 27 Canis Majoris* is derived from observations covering the years 1925–1931. The period is 2000 days or longer and the amplitude is 220 km/sec. The *minimum mass is 2000*⊙.

The *double bright components of the hydrogen lines show variations* in intensity which are probably related to the period of the velocity-curve. No emission could be seen in lines of other elements (helium, magnesium, silicon, or carbon).

The *absorption lines show striking changes in intensity*, which are also related to the period of the velocity-curve. They are weakest at the time of maximum velocity, and appear greatly strengthened when the velocity is at minimum.

Several years ago the spectroscopic binary 27 Canis Majoris, of class B5, was found[1] to have a velocity-curve of large amplitude and of unusually long period, indicating a very large mass. Spectrographic observations of this interesting star have been carried on at the Yerkes Observatory for the last six seasons; the resulting velocity-curve is shown in Figure 1, and the recent individual measures are given in Table I. The earlier observations have been published in the papers above referred to. In the course of five and one-half years the radial velocity has undergone a variation from about +120 km/sec. to −100 km/sec. and back to +120 km/sec. A variation of shorter period—approximately 100–120 days—is superimposed upon this curve and has an amplitude of approximately 40 or 50 km/sec. The observations are perhaps not sufficiently numerous to permit a detailed study of this shorter variation. Attention should,

[1] *Astrophysical Journal*, **65**, 273, 1927; **66**, 113, 1927; **68**, 109, 1928.

however, be called to the fact that the appearance of a short-period oscillation with amplitude smaller than that of the long-period curve is quite unusual.

The long-period curve in Figure 1 suggests that the period cannot be less than about 2000 days.[1] Unfortunately, the early observations are scanty, and in view of the existence of the secondary fluctuation, it is not possible to combine satisfactorily into one curve all

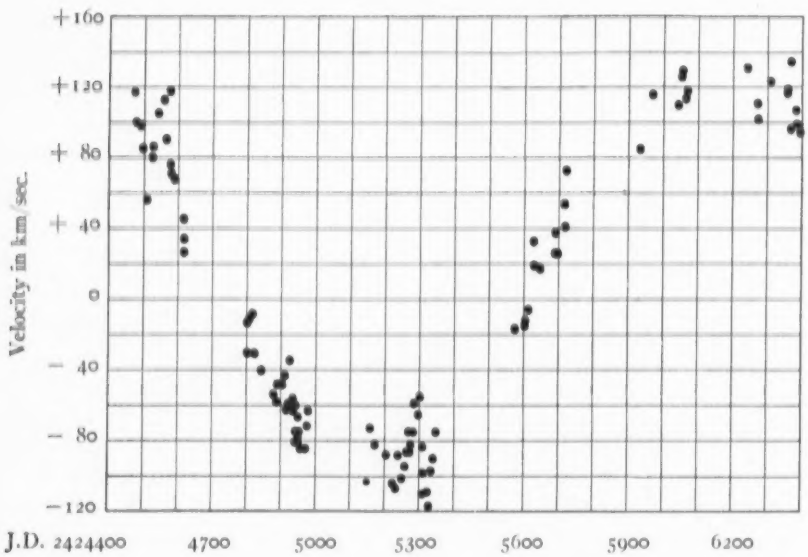


FIG. 1.—Velocity-curve of 27 Canis Majoris

available radial velocities of date earlier than 1925. Through the kindness of Dr. J. H. Moore I was permitted to measure two spectrograms which had been taken at the Lick Observatory by Dr. P. W. Merrill for his study of the bright *Hα* line.[2] My measures of these plates given in Table II are somewhat uncertain, since the spectrograms were not intended for accurate measurement, but the agreement of velocities derived from different lines is sufficiently satisfactory, and the average value from the two plates should at least

[1] Several long series of observations made by F. J. Neubauer at the Lick Observatory station in Chile have shown that the period cannot be of the order of one day (see *ibid.*, **68**, 110, 1928).

[2] *Lick Observatory Bulletins*, **7**, 170, 1913.

roughly indicate the velocity of the star in December, 1912. An attempt to fit a period of 2000 days into the old observations gives a minimum of radial velocity in 1911. This agrees reasonably well

TABLE I

RADIAL VELOCITIES OF 27 CANIS MAJORIS

| Date | G.C.T. | Observer | Quality | Vel. I Km/Sec. | Vel. II Km/Sec. |
|---|---|---|---|---|---|
| 1928 Nov. | 24.404 | Lv, Hu, S | f | − 16 | ..... |
| Dec. | 22.278 | P, S | f | − 15 | ..... |
| Dec. | 24.338 | Lv, S | g | − 12 | ..... |
| 1929 Jan. | 2.271 | P, S | g | − 6 | ..... |
| Jan. | 16.260 | Lv, P, S | p | + 33 | ..... |
| Jan. | 19.215 | P, S | g | + 19 | ..... |
| Feb. | 3.220 | Lv, Hu, S | g | + 17 | ..... |
| Mar. | 18.046 | P, M | p | + 38 | ..... |
| Mar. | 21.065 | B, P, S | f | + 26 | ..... |
| Mar. | 27.088 | B, P, S | g | + 26 | ..... |
| Apr. | 14.077 | B, P, S | p | + 56 | ..... |
| Apr. | 16.066 | B, P, S | f | + 41 | ..... |
| Apr. | 19.072 | Lv, P, S | p | + 73 | ..... |
| Nov. | 16.424 | σ, S | f | + 85 | ..... |
| Dec. | 22.311 | σ, S | p | +116 | ..... |
| 1930 Mar. | 6.094 | σ, R, S | f | +110 | ..... |
| Mar. | 16.092 | σ, S | p | +126 | ..... |
| Mar. | 20.082 | σ, Hi, S | f | +130 | ..... |
| Mar. | 28.090 | Hi, R, S | f | +114 | ..... |
| Apr. | 3.069 | Hi, S | p | +118 | ..... |
| Sept. | 22.448 | σ, S | f | +132 | −124 |
| Oct. | 22.471 | σ, S | g | +111 | ..... |
| Oct. | 25.444 | M, S | f | +102 | ..... |
| Nov. | 28.383 | σ, Sch, S | f | +124 | ..... |
| 1931 Jan. | 16.228 | M, S | g | +119 | ..... |
| Jan. | 17.238 | σ, M, S | g | +117 | −178 |
| Jan. | 25.281 | Sch, S | p | +135 | ..... |
| Jan. | 26.278 | Sch, S | g | + 96 | ..... |
| Feb. | 9.238 | σ, S | g | +107 | ..... |
| Feb. | 14.161 | σ, S | p | + 99 | ..... |
| Feb. | 22.140 | σ, S | g | + 94 | ..... |

The following abbreviations are used: B=S. B. Barrett; Lv=C. T. Elvey; Hi=C. D. Higgs; Hu=C. Hujer; M=W. W. Morgan; P=A. Pogo; R=F. E. Roach; Sch=H. Schwede; S=F. R. Sullivan; σ=O. Struve; g=good; f=fair; p=poor.

with the large positive values measured at the Lick Observatory in 1909 and 1910, but it leaves the velocities obtained from the plates of Merrill rather far above the curve. In order to verify the velocities obtained formerly from three early Yerkes plates, I have remeasured them, and the results are given in Table III. The agreement is as

good as could be expected considering the character of the spectrum of this star.

As I have mentioned in my former papers, the hydrogen lines of 27 Canis Majoris show bright components. These have not been measured, but in the case of $H\beta$, where the bright line is sufficiently strong

TABLE II

LICK OBSERVATORY PLATES

| Date | Observer | Radial Velocity Km/Sec. |
|---|---|---|
| 1912 Dec. 2 | Merrill | +100 |
| Dec. 11 | Merrill | + 70 |

to be visible on many plates, it appears to consist of two components, the relative intensities of which vary with the period of the binary. This is a phenomenon well known in other stars, such as $\varphi$ Persei, where the bright lines are much more pronounced than in 27 Canis Majoris. In the latter the violet component is strong when the radial

TABLE III

YERKES OBSERVATORY PLATES

| Date* G.M.T. | I Measure Km/Sec. | II Measure Km/Sec. |
|---|---|---|
| 1907 Feb. 16.64 | +48 | +50 |
| Feb. 22.64 | +43 | +40 |
| 1916 Oct. 16.97 | +22 | + 9 |

* The dates of the first thirteen observations given in Table I, *Astrophysical Journal*, **65**, 279, 1927, were in error, with the exception of 1908 Nov. 10, which was given correctly. In order to reduce the remaining twelve dates to the new G.C.T. (counted from midnight) add 1.00 days to the values given there. This does not affect the results.

velocity is positive and the red component is strong when the velocity is negative. The intensity of the red component when strongest is somewhat greater than the intensity of the violet component at its maximum strength.

This correspondence between the intensities of the bright component of $H\beta$ and the radial velocity might suggest that the measured changes in velocity are not real, but merely produced by the variation in the bright components. It should be noted, however,

that the radial velocities depend mostly upon the lines of helium, which seem to show no emission, though they do show a pronounced doubling.[1] Furthermore, I have frequently measured the magnesium line λ 4481, and have found it to agree in velocity with the helium lines. Since the magnesium line almost never appears in emission in Be stars, this speaks strongly against the above-mentioned possibility. It is well known that the bright components decrease rapidly in intensity along any one series. In hydrogen I have seldom been able to see any emission in $H\gamma$, and never in $H\delta$. Nevertheless, $H\beta$, $H\gamma$, $H\delta$, and $H\epsilon$ appear to give consistent radial velocities. The same is true of several helium lines belonging to different series.

In order to test this matter further, I have taken several spectrograms of 27 Canis Majoris, during the past season, on Eastman Process plates having a strong contrast factor. A developer of high contrast (D11) was used, in order to bring out the emission components. Although the absorption lines appear in great intensity on these plates, I am unable to see any emission except in the hydrogen lines. On the best of these spectrograms I measured *Si* II 4128, *Si* II 4131, *Fe* II 4233, *C* II 4267, *Mg* II 4481, *Fe* II 4550, and the velocities obtained from these lines agree well with those derived from the helium lines. The evidence would thus seem to be against any explanation involving the apparent effect of the bright lines.

A point of great interest is that the absorption lines show striking changes which are apparently related to the velocity-curve. In the season of 1925–1926 the principal components of the double absorption lines had a large positive velocity, and they appeared rather weak and diffuse, though not as weak as the fainter violet components. In the following season, 1926–1927, the velocity was intermediate, and the intensities of the principal components were slightly stronger than they were in the preceding season. In 1927–1928 the principal components of all lines were very strong, and their position in the spectrum approximately coincided with that of the fainter components in 1925–1926. On the other hand, the fainter components in 1927–1928 were rather weak and coincided in position with the stronger components as they were in 1925–1926. In 1928–1929 the lines resembled those of 1926–1927, and in 1929–1930 and

[1] *Astrophysical Journal*, **65**, 273, 1927.

1930–1931 they were again similar to those of 1925–1926, both in appearance and in position in the spectrum. The changes in intensity affect all absorption lines of helium and of hydrogen to about the same extent, and do not appreciably alter the spectral type of the star. However, I am not certain that the lines of other elements, such as magnesium λ 4481, are strengthened in proportion. The spectrum is dominated by the lines of hydrogen and of helium. It should be noted that while in ordinary spectroscopic binaries with double lines the intensity is greatest when the two spectra coincide, this is not the case in 27 Canis Majoris. The observed variations must therefore be due to real physical changes in the star.

TABLE IV

ORBITAL ELEMENTS OF 27 CANIS MAJORIS

| | |
|---|---|
| $\gamma =$ | $+25$ km/sec. |
| $P =$ | 2000 days |
| $T =$ | 2424990 J.D. |
| $\omega =$ | $147^\circ$ |
| $e =$ | 0.12 |
| $K =$ | 110 km/sec. |
| $\frac{m_2^3}{(m_1+m_2)^2} \sin^3 i =$ | $275\odot$ |
| $a \sin i =$ | $3\times 10^9$ km |

It should be noted, in this connection, that 27 Canis Majoris is not definitely known to vary in brightness, although it was suspected by Gore.

The changes in the absorption lines may be similar to those found in 17 Leporis,[1] in $\alpha^2$ Canum Venaticorum,[2] and in B.D.-18°3789.[3] All of these stars show variable absorption lines, not accompanied by changes in the brightness of the star. It seems difficult to explain such variations on the basis of existing theories for the formation of stellar absorption lines.

If we treat the star as a spectroscopic binary, we find, from the curve in Figure 1, the elements given in Table IV. The value of the

[1] Struve, *ibid.*, **72**, 343, 1930.

[2] H. Ludendorff, *Astronomische Nachrichten*, **173**, 1, 1906; A. Belopolsky, *ibid.*, **196**, 1, 1913.

[3] W. W. Morgan. Unpublished.

period remains somewhat uncertain and should be regarded as a lower limit only.

The mass function, Table IV, is 275 times the mass of the sun, and consequently the minimum total mass of the whole system is approximately 2000$\odot$. This is about twice the value given in my first paper,[1] the difference being due almost entirely to the fact that the period is much longer than I had at that time supposed. The value of the mass so far exceeds that of any other binary known that it would be advisable to exclude it, for the time being, from any statistical discussions of spectroscopic binaries. While we have as yet no indication that the observed changes in radial velocity are not due to orbital motion, we should be open to the alternative that they have some other, perhaps unknown, cause.

The fainter component of the spectrum, although measured on two plates only (Table I), could be seen or suspected on several other plates.

YERKES OBSERVATORY
March 5, 1931

[1] *Ibid.*, **65**, 273, 1927.

# ATOMIC SYNTHESIS AND STELLAR ENERGY. II

By R. D'E. ATKINSON

ABSTRACT

A *synthesis theory of stellar energy and of the origin of the elements* is developed, in which the various chemical elements are built up step by step from lighter ones in stellar interiors, by the successive incorporation of protons and electrons one at a time. The essential feature is that *helium*, which cannot well be formed in this way, is supposed to be *produced entirely indirectly*, by the spontaneous *disintegration* of unstable nuclei which must first themselves be formed.

A formula for the *probability of penetration of nuclei by protons* is derived from the *wave-mechanics;* it is a correction of one previously given, but agrees with that in showing that with any approach at all to the observed absolute amounts of the lighter elements *very high temperatures in normal stellar interiors are impossible.* The *model* must be approximately that *of Eddington*, but with Jeans's modification to take account of Kramers' formula for the absorption coefficient. Russell's value for the hydrogen content reconciles this formula with astrophysical data.

The low temperature and the relative amounts of the heavier elements make a *second synthesis process for protons* unavoidable; this is assumed to exist, and to possess arbitrary but extremely simple properties with no special features at any particular element. The possibility of *incorporation of electrons*, when "room" has become available, is taken for granted.

The elements whose *disintegration* supplies helium are in all cases either *those known* (or strongly suspected) to be unstable, or those isotopes, unknown now, *whose instability follows from Gamow's theory* of mass defects.

The *rate of formation of helium* must be nearly *constant*, in any one star, throughout most of its lifetime. The law of mass action demands then that all stars, after a marked *initial contraction and rebound*, should spend the greater part of their lives very *slowly expanding*. The constancy of the helium supply can be guaranteed, in the main sequence, if the average life of oxygen, until further synthesis, is about equal to the past lifetime of the star. This leads to *central temperatures* which can be calculated for the sun and estimated for other stars. The figure for the sun is *16,000,000°*, which is in *good agreement with* that calculated for *a polytrope* of index about 3 and constitution somewhat over 50 per cent hydrogen. The increase necessary for heavier stars can be covered by a small systematic change in the polytropic index. The main sequence is thus accounted for.

The *relative proportions of the elements* in stars of the main sequence follow from the theory, in *excellent qualitative agreement* with Russell's figures for the sun. The scarcity of the lightest elements, the principal maximum at a fairly early point, a minimum before the iron group, a maximum in it, a scarcity of all elements above it, and minor maxima in the barium and lead regions all follow without any special assumptions, from Gamow's theory of nuclear stability, owing to the peculiarities of the Aston mass-defect curve.

For the *low-density giants* some *earlier source of helium* must be operative. This is taken to be $Be^8$, whose instability was already assumed by F. G. Houtermans and the writer, and has since acquired almost the status of observational fact. It must be long-lived, since it is found on the earth, and this *accounts for the Hertzsprung gap* and its continuation between the Cepheids and B stars, and for the fact that $Be^8$ cannot supply helium in the main sequence. In giants it can supply enough helium, and even the brightest red supergiants can exist on the *He–Li* synthesis given by the wave-mechanics alone, with *central temperatures less than 4,000,000.°* This figure can be reached on Eddington's theory by a systematic change in the polytropic index which is considerable but not prohibitive.

All *very diffuse giants* should be *variable*. The occurrence of *R- and N-type stars* among giants is accounted for, and also their absence among dwarfs. For the *Cepheids* an *explanation of Eddington's* has become plausible, owing to the adoption of the vary-

ing polytropic index. There should be *more very bright G and M stars* than K ones, and the *concentration of the M stars round magnitudes — 5 and 0* can be accounted for. The occurrence of *coeval pairs* in which the *brighter is the cooler* is in entire agreement with the theory, as is the fact that the brightest stars in *clusters* are usually *all red or all blue*. The fact that *stars of small mass are all on the main sequence* (unless they are white dwarfs) can be explained. Various minor observations also seem to fit the theory.

*White dwarfs* follow from a *theory of Rosseland;* electrostatic forces will drive the hydrogen from the center of a star if it is not very abundant. They thus represent the final stage. The absence of hydrogen prevents generation of energy and they contract to a high density and temperature. Their energy may be purely gravitational, but need not be so. The *faint O stars* in planetary nebulae should all be "white dwarfs" generically.

The synthesis process predicted by the wave-mechanics is very sensitive to temperature; it is shown that *main-sequence stars* will nevertheless probably not be "*overstable.*"

A number of *arguments for and against older theories* are discussed. Jeans's theory of the eccentricities of binaries need not demand a long time-scale if the galaxy is expanding as fast as the universe in general is.

A *new notation* is introduced for rapid approximate calculations. It is convenient to use and cheap to print.

## 6. STELLAR TYPES AND MAGNITUDES

### C. THE GIANTS

i) *The problem.*—The essential characteristic of the giants[1] has proved a stumblingblock to many previous attempts at suggesting a source for stellar energy; they have a high rate of radiation, and presumably always have had it, so that their material should be more "exhausted" than that of the sun unless they are all very young, and yet they contrive still to develop energy at this rapid rate although their densities and internal temperatures are relatively low. Eddington pointed out[2] that the difficulty is particularly acute in the case of double stars (and of members of a cluster), in all cases in which the more luminous star of a pair has also the lower density, since the assumption of inequality in the ages is very unattractive here; the situation actually arises with a large proportion of all visual binaries, as may be seen from an analysis by Leonard.[3]

The only theory that seems as yet to have overcome the difficulty, even by deliberate *ad hoc* assumptions, is one due to Russell,[4] who

[1] Since Milne's theory has made the word "diffuse" applicable to densities inferred by Eddington for the main sequence, it seems convenient to restrict the word "giant" to bright stars more diffuse than main-sequence ones of the same mass, so that bright B and O types are not included. The word will always be used in this sense in what follows.

[2] Eddington, *The Internal Constitution of the Stars*, p. 297.

[3] *Lick Observatory Bulletin*, No. 10, p. 189. 1921.

[4] Russell, Dugan, and Stewart, *Astronomy*, pp. 909–13. (Not available in periodicals.)

postulated a "giant stuff" and "dwarf stuff"—two different sources of energy dependent in a different way on the temperature and density; the dependence was assumed to be such that the "giant stuff" was used up first if the star's mass was large, and was not tapped at all[1] if it was small; this comes in effect remarkably close to the situation that actually follows from our assumptions.

ii) *A new source of helium.*—On our theory the direction in which a solution is to be sought is at once apparent. Enough energy will be generated even at fairly low densities and temperatures if there is enough helium present. It becomes necessary then to find a source of helium that can be replenished at temperatures at which the "hill" in the oxygen region is quite unsurmountable; the source must also go out of action at higher temperatures. The main course of the nuclear energy-curve for no free electrons (Fig. 1) is evidently downward from carbon to argon, so that all these elements ought to be stable; instability may however also arise if the ordinate of the curve is positive, and this may occur at $Be^8$. The mass defect of $Be^8$ is not known yet (the element itself has only recently been discovered), but it may be estimated by extrapolation and will evidently be nearly zero. It is not really possible to estimate whether it should be positive or negative; but if it is "negative" (i.e., if the ordinate in Fig. 1 is positive), $Be^8$ will be unstable; it will tend to break up into two α-particles, with no other residue.

The assumption that this is in fact the case was made by Atkinson and Houtermans before the existence of $Be^8$ was known of, and it at once received some experimental support. Lord Rayleigh pointed out[2] that many terrestrial *Be* minerals had already been found by him[3] to contain an altogether unaccountably large amount of helium, and he suggested that this might be the disintegration product of the $Be^8$ that had been trapped in the minerals when they crystallized out. His measurements have since been confirmed by Paneth and Peters,[4] and no alternative explanation of them seems as yet to have been suggested.

[1] Or, at least, not until the white dwarf stage was reached.

[2] *Nature*, **123**, 607, 1929.

[3] R. J. Strutt, *Proceedings of the Royal Society*, **80**, 572, 1908.

[4] *Zeitschrift für physikalische Chemie*, Abt. B, **1**, 187, 1928.

If the unstable isotope lived long enough to be still present when these minerals, some of which do not appear to be very old, crystallized out, one would expect that it should also be possible to detect it by the sensitive band-spectrum method even at the present time, and it is accordingly satisfactory that this has now been done.[1] The relative proportions of $Be^8$ and $Be^9$ are estimated, admittedly with some uncertainty, at about 1 to 2000, and the amount of helium found in minerals corresponds, in favorable cases, to more than one atom for every 10,000 $Be^9$ atoms, so that we may assume without difficulty that the crystals in such cases have existed somewhat less than the half-life of $Be^8$. An average life of about $10^{8.5}$ years would be in fair harmony with this, and this turns out to be satisfactory for the giant stars. Moreover, if Gamow's theory of radioactivity[2] can be applied to a "conglomerate" of only two $\alpha$-particles, so long a life as this would mean (since $Z$ is forty times smaller than for ordinary radio-active atoms) a disintegration energy (and mass defect) of almost exactly zero.

While then it cannot yet be claimed that the instability of $Be^8$ has been proved, the absence of any other explanation for the helium in beryls makes it plausible; and the fact that a figure can then be assumed for its average life which harmonizes reasonably well with the $Be^8/Be^9$ ratio, the $He/Be$ ratio, its (extrapolated) mass defect, and the properties of giant stars is fairly strong support. We therefore explicitly add to our fundamental assumptions the postulate:

V. $Be^8$ disintegrates with a period of about $10^{8.5}$ years.

iii) *Theory of giant stars: "red" and "blue" clusters.*—It is clear that this will be quite irrelevant at the center of a star of the main sequence; the synthesis time of the $Be$–$B$ step is too short for $Be^8$ atoms to decay often under such conditions. If $Be$ is formed, as it might be, in cooler regions also, the case will be different—we shall return to this point later. For the present we confine our attention to stars in which boron cannot readily be formed, i.e., stars cool enough to allow the disintegration of $Be^8$ to occur. How they become

[1] Watson and Parker, *Physical Review*, **37**, 167, 1931.

[2] *Zeitschrift für Physik*, **51**, 204, 1928; Atkinson and Houtermans, *ibid.*, **58**, 478, 1929, etc.

so cool, after their initial contraction, is a question we shall also take up later.[1]

Roughly, the same sort of argument applies to these stars as we have used in the main sequence; but the guaranty of stability, and indeed the maximum possible lifetime, seem to be less. The part previously played by $Ni^{56}$ is now played by *He* itself; the piling-up of the products of synthesis will therefore take a somewhat different course now, since there is obviously no possibility at all of building a "wall" at the elements of longest life and before the helium-producing cycle. In fact, the rate of production of helium will be proportional, at a given temperature, to $N_H N_{Li}$ as long as all the $Be^8$ formed from *Li* has time to decay again; this product must vary considerably, since all the *He* formed passes on to *Li*, and each $Be^8$ atom turns into two *He* ones, and it thus appears doubtful whether any very long-continued existence without change of type is possible for very diffuse stars.

In effect, the same has been assumed in most previous theories, and of course it creates no particular difficulty. At very worst, no contraction can be more rapid than that of Helmholtz-Kelvin; and while we cannot be so sure about expansions, there is no reason at all to anticipate that they should occur with a directly observable rapidity except in a star's very early history. At most, then, the comparative impermanence of the giants might involve some statistical difficulties, but in fact the position is quite the contrary; it seems to have positive advantages.

Our theory is in this respect a physical filling-in of the outline already suggested by Russell to account for the energy of giants and dwarfs. He supposed that a massive star first contracted until it reached temperatures at which its "giant stuff" became active, and that when this had been used up it contracted further until its temperature allowed the "dwarf stuff" in it to generate energy; in this stage it would be a B or O star. Thus a postulate of roughly a common age for all the stars of a cluster was sufficient to explain why in some clusters the brightest stars are all red and in others all blue,[2] while mixtures do not seem to occur, except among less

[1] § 6, *C*, vii.

[2] R. J. Trumpler, *Publications of the Astronomical Society of the Pacific*, **37**, 307, 1925.

bright stars; these might be drawing on both energy sources simultaneously.

In Russell's theory the "giant stuff" and "dwarf stuff" were supposed to be separate substances, each capable of exhaustion without affecting the other. And they were supposed to differ in the dependence of their activity on temperature. In our theory there is no adequate place for these specific ideas; the star generates its own "fuel," and it generates the same fuel (helium) and "burns" it in the same atmosphere (hydrogen), whatever its physical condition. But we nevertheless obtain all the practical advantages of Russell's theory, because our stars have two different machines for producing fuel, $Zn^{60}$ and $Be^{8}$, and the latter is not only one which can be "turned on" by moderate temperatures, but one which must be turned off again by high ones. (The instability of $Be^{8}$ is perhaps still only an assumption, but its long life is certain.) Clearly this will not merely simulate a process in which the actual dependence of the generation of energy on temperature is different from that of the other, but will also produce the appearance of "exhaustion"; a star that has had to raise its temperature beyond a certain point will obtain no more helium until it contracts enough to bring it to the main sequence, and Russell's theory of "red" and "blue" clusters can be taken over, with only this change, into the present one.

iv) *The Hertzsprung gap and the Cepheids.*—The temperature at which the helium supply is throttled will be one such that the average value, through the whole star, of the synthesis constant for the *Be–B* step is about equal to the natural disintegration constant of $Be^{8}$. If half the $Be^{8}$ atoms are converted to *B* before they break up, the supply of *He* will just remain constant; but as this will not happen until the star has already contracted a considerable amount, owing to diminution of the hydrogen supply, a constant helium production will no longer meet the case and the star will have to contract further. As soon as less than half the $Be^{8}$ atoms disintegrate, the amount of helium falls as well, and a still more rapid contraction puts an end to the giant stage.

Thus we do not expect the giants to run continuously into the main sequence; there will be a gap between, in which stars are contracting fairly rapidly and therefore are comparatively rare, though

not entirely absent. Qualitatively at least this is an explanation for the "Hertzsprung gap"; and apparently it will account also for the entire gap between the Cepheids and the main sequence, though it does not seem to yield an explanation for the Cepheids themselves. Quantitatively, it is difficult to be sure in the region of very large masses, but we may work out the average life for the *Be–B* synthesis in the Hertzsprung gap proper, and compare it with the assumed disintegration period of $Be^8$.

From the diagram we estimate the central temperatures of stars in the gap to be anything down to about 0.4 of that of the main sequence, which latter might be 18,000,000° at these masses; we shall therefore set $T=10^{6.86}$. The mean densities are clearly between $10^{-1.0}$ and $10^{-2.0}$. The concentration of mass to the center is not very certain, but should be somewhat greater than in the sun; we may put the central density at perhaps thirty times the mean (the exact figure is unimportant). Since we are supposing that stars in this position are beginning to be seriously short of hydrogen, we shall put the proportion of hydrogen at three-fourths by volume, or say one-sixth by weight (probably most of it has been converted into elements lighter than nitrogen). Thus the number of protons at the star's center is ant.$(-1.8+1.5-0.8+23.8)=10^{22.7}$; their most probable velocity, $v_0$, is $10^{7.5}$.

It follows that, for *Be*, $\xi=$ ant. $\frac{1}{3}(4.73+0.60-6.86/2)=4.30$, and $\log\lambda=-5.5-7.5+22.7+0.6-55.6/2.3=-13.8$; the average life of a *Be* nucleus, until the boron synthesis, is then ant. $(13.8-7.5)=10^{6.3}$ years.

At first sight this appears appreciably too short, but one important correction may remain. For, just as was the case in the main sequence, if there is a considerable amount of mixing we shall have to multiply this figure by a factor of perhaps 100 in order to allow for the fact that most of the $Be^8$ atoms will be at temperatures so low that there will after all be time for their disintegration. Of course, mixing may be inadequate to produce this result completely in $10^{6.5}$ years; but the assumption that the temperatures of these stars, inferred from Figure 3, do not rise above 0.35 of those in the main sequence would be enough to lengthen the calculated period to

$10^8$ years with no mixing. The data are scarcely adequate to decide between the fractions 0.35 and 0.40.

If we regard the gap between the Cepheids and the main sequence as a continuation of the Hertzsprung gap, and neglect the fact that the Cepheids are variable, the theory can give a qualitative account

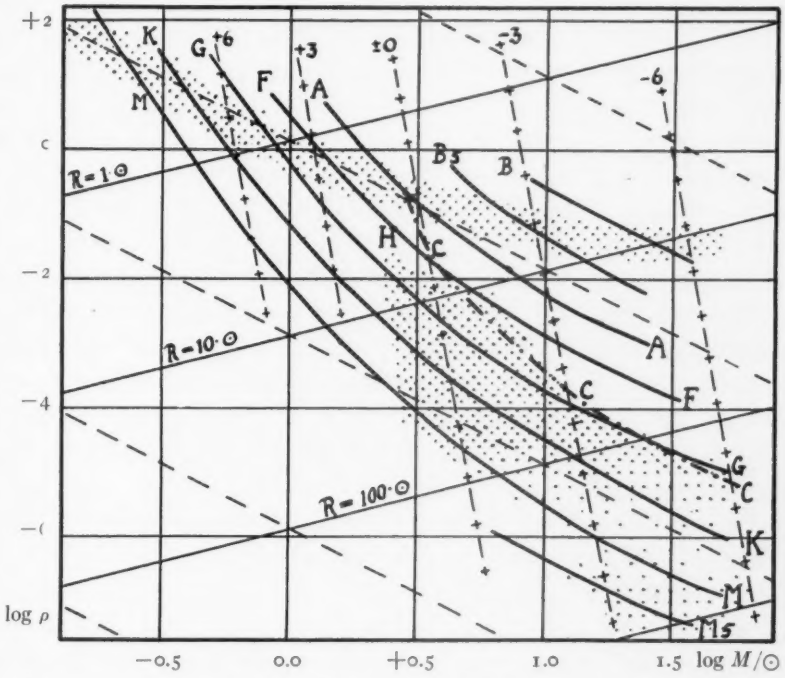


FIG. 3.—Stellar types and magnitudes. The dots indicate the supposed distribution if all stellar masses were equally common. *C* denotes the Cepheid line, *H* the Hertzsprung gap.

of the facts here also, always supposing that the polytrope index increases somewhat with the mass. For then the central temperatures along the edge of the gap (apparently this is nearly the same as "along the Cepheid line") will be nearly constant, instead of decreasing with increasing mass; in fact, reference to Figure 3 shows that if $\beta$ remains nearly unity at large masses the temperatures may indeed even rise slightly; this is the situation we should require.

The main sequence is determined by the condition that the aver-

age life of oxygen should be comparable with that of the star, and therefore should be falling considerably at the higher masses; the edge of the "Cepheid gap" is determined by the condition that the average life of beryllium (until synthesis) should be equal to its disintegration period, and this is constant. Thus the edge of the gap should be occupied by stars whose central temperatures, though they rise in order to counteract the falling densities, do not rise as fast with the mass as in the main sequence. This is evidently approximately the case in fact, but it is difficult to decide whether the agreement is really satisfactory. There seems, however, no doubt that the width of the gap should at least increase with increasing mass, especially since the central densities are becoming larger multiples of the mean ones as the mass goes up.

On this view such stars as $\alpha$ Cygni, $\alpha$ Carinae, and Rigel are in a transition stage, probably contracting comparatively fast. Their energy will be supplied partly by gravitation, but the beryllium and boron that were left in existence when they began this stage can be built up gradually as the temperature rises. We should perhaps expect to find such stars in appreciably greater numbers at the lower masses.

We have now accounted broadly for the distribution of the stars in this part of the diagram, but not for the circumstance that the Cepheids themselves are variable. In fact, no immediately obvious way of connecting their variability with the processes of energy generation seems to suggest itself, and it appears preferable to adopt a proposal of Eddington's, according to which the occurrence of a particular stage of ionization is responsible. In favor of this alternative is the fact that the "cluster variables" appear to lie on the other side of the Hertzsprung gap, practically in the main sequence, and seem to have varying central temperatures at constant mass. The gap between the cluster variables and the typical Cepheids can be explained as we have explained the Hertzsprung gap (with which it seems to coincide) only if the process of helium-generation is different for the two groups; in that case the variability is probably not directly due to any peculiarity in the energy generation.

On Eddington's view,[1] pulsations could be maintained in a star

[1] *Op. cit.*, p. 202.

if the absorption coefficient increases with compression, and he suggested that the loss of most of the *L*-electrons by a group of the commonest elements might produce such a situation at a critical point in a star's development. In our case the commonest elements are difficult to place, in such stars, but qualitatively the theory seems suited none the less. If it is to hold, the central temperatures must fall slightly, as we pass to larger masses among the Cepheids.

The Cepheids appear to lie on a very narrow line in Figure 3. The values plotted are taken directly from Eddington,[1] and the narrowness may in fact be merely a result of the circumstance that the luminosities were obtained from the luminosity-period curve and the masses then from the mass-luminosity curve; the points would not lie on a line if it were not for the correlation of period and type in addition, but this correlation seems to follow from the other two if we grant the law $\Pi V \rho = \text{Const.}$ an equal validity. Thus the effect may not be entirely real. On our theory, however, we should expect it to be quite real, because differences in constitution and in molecular weight are the only plausible widening influences for the line, and according to our theory these are absent; at any one mass the particular density involved is reached only when the hydrogen exhaustion has attained a definite figure.

A sudden change in the ionization might have other important effects in our theory, besides causing a change in the absorption coefficient. If, as we shall see may perhaps be the case, the rate of diffusion of light elements through the star were an important factor in its energy control, the loss, on the part of a group of abundant elements, of most of their *L*-electrons might change the mean free paths and produce new conditions. A star which was just able to maintain its equilibrium beforehand might find itself in difficulties afterward, and a giant star is nearly bound to head for the main sequence if it gets into difficulties. This would not of course explain the Cepheids in themselves, but it could be an additional ground for the fact that the gap begins just above them, and might therefore account for the fact that they do seem (among the giants) to form the boundary of the gap.

v) *Giants and supergiants: long-period variables.*—We have sup-

[1] *Ibid.*, p. 182.

posed that even the giants are steadily maintaining their supply of helium. For the heaviest ones, however, this view is not necessary, and we can probably abandon it for the most diffuse ones at all masses, without causing any difficulty. A star that formed, during its early expansion, a large amount of radioactive atoms such as $Be^8$ would have a very considerable helium supply during the lifetime of that element, but of course not much longer. In fact, if the star is really cool inside (and a great excess of $Be^8$ would force it to become so), the helium need no longer even be locked up in *Be* nuclei at all; it may be completely free.

We should thus expect giants, perhaps at any mass but at least at large ones, to be concentrated about two central temperatures, or, owing to Lane's laws, to be concentrated in two spectral types, with a gap between. At the lower temperature there is a large amount of free helium (possibly being replenished by radioactive substances, but possibly not), and the *He–Li* synthesis is the only one occurring; at the higher temperature the concentration of *He* is less, the *He–Li* and *Li–Be* syntheses are both occurring, and the *He* is presumably being replenished from $Be^8$.

Observationally, this situation does not seem to have been definitely verified as yet, but there is one quite favorable indication. The M stars have been found[1] to be apparently concentrated into two groups, with absolute magnitudes about 0 and $-5$, respectively. It is obvious that this would probably also follow from our theory, although here again a comparison of stars of different masses (and the same spectra) is much less satisfactory than a comparison of stars of the same mass (and different spectra). We should, however, regard the M supergiants as relying on the *He–Li* synthesis alone, and the M giants and G supergiants as relying on the full regenerative "giant cycle," and our theory leads us to expect a scarcity of bright K supergiants, as compared with the classes M and G. It is not improbable that this should actually be found.[2]

We may calculate the central temperature that a red supergiant would need, if its energy were to be provided by the *He–Li* synthesis

[1] Strömberg, *Astrophysical Journal*, **72**, 117, 1930.

[2] Strömberg, *ibid.*, **73**, 40, 1931, has shown that there are few K stars as bright as the majority of the brightest M ones.

alone. It appears that a fairly large concentration of both hydrogen and helium is necessary, and that even so the temperature tends to come out rather high. Nevertheless, until the question of the model has been more thoroughly investigated, it cannot be ruled out as impossible.

We pick a star of mass $30\odot$ and mean density about $10^{-7}$; this might perhaps be an M5 supergiant of absolute magnitude $-6$. Such cases are not common, and we may perhaps allow the rather exceptional proportion of 10 per cent of helium by weight, and 80 per cent of hydrogen. The concentration of mass toward the center is presumably high, so that the mass whose temperature is a high-enough fraction of the central temperature is also relatively large, possibly 6 or 7 per cent of the total. Thus the number of *He* atoms in this "active volume" will be ant. $(33.3+1.5-2.2-0.6+23.8) = 10^{55.8}$. The total number of syntheses per second for a star of this brightness is ant. $(38.5+0.40\times 10.85) = 10^{42.8}$, so that the *He* atoms must have an average life of $10^{13.0}$ seconds, if they were kept in the active volume. The number of protons/cc (if the central density is two hundred times the mean) is ant. $(-7.0+2.0-0.1+23.8) = 10^{18.7}$, and their most probable velocity $v_0$ is perhaps $10^{7.4}$. Thus, from (3), $-13.0 = -5.5-7.4+18.7+\log \xi - 3\xi^2/2.3$, so that $\xi = 3.86$, and, from (4), with $Z=2$, $T = 3.5 \cdot 10^6$ degrees.[1]

From Figure 3 a star of the type considered would have a central temperature about twenty times less than that of the sun if $\mu$, $\beta$, and $n$ were the same as in the sun. Probably $\mu$ will be much the same; $\beta$ will be less, which is disadvantageous, but will not be much less if $n$ is appreciably more. The temperature that we have found is only about $4\frac{1}{2}$ times less than in the sun, so that there is a factor of about 4 or 5 to be taken care of by changes in $n$ alone. This is obviously serious but not necessarily fatal. It is conceivable that there may be systematic changes of $n$ with radius, as well as with mass. The question needs further investigation.

However, we have now dealt with the most difficult case that seems likely to arise. If changes in the model are adequate to account for this case, we may claim to have explained all the giants.

[1] The equations are on p. 293 of Part I; equation (5) precedes them, owing to an unfortunate oversight.

Moreover, if we omit the question of their constitution, these stars, the coolest internally of any, do not need process B at all; here, where process A is less effective than anywhere else, it is still adequate, as far as energy generation goes, for even the brightest stars.

It is clear that these very diffuse giants cannot have very long lives, since they have no means of adding to their helium sources. If in addition there are no sources, the life of the star we have been considering will be only about $10^{5.5} \times 100/7$ years in the very diffuse state. If we drop the fraction of hydrogen to 40 per cent by weight (which will not seriously affect the calculations) we can admit the possibility of a fair proportion of $Be^8$ as well; each $Be^8$ atom provides two *He* atoms, and each *He* atom can presumably be used twice ($He^4$–$Li^5$ and $He^5$–$Li^6$; unless $Be^6$ could exist this is the only possibility), but even so it is clear that the lifetime in the diffuse state cannot be very long. It must be remembered, however, that even the total lifetime of these very heavy stars is not long; it is, in fact, hardly as long as the period of decay we have assumed for $Be^8$.

The possibility that if the mass is greatly concentrated to the center, even gravitational energy may become important, should not be forgotten. But whatever we do, we cannot avoid the view that at least white dwarfs and red supergiants must be of somewhat widely differing ages, and the clusters whose brightest stars are predominantly red seem to be foredoomed to a short life in that state, however we modify our theory. Unquestionably the difficulties are least when the masses of the heavy stars are concentrated strongly toward their centers; if in addition the masses should be too large for the *M-L* relation, this will also help a little.

A star consisting of hydrogen and a large amount of free helium would be "overstable," and could hardly avoid falling into pulsations; thus our theory automatically provides for the long-period variables. This point will be further dealt with below;[1] its importance here lies in the fact that in a pulsating star the periodic change of central temperature is quite considerable, and may allow a sufficient generation of energy intermittently even if the average temperature would be inadequate. Those stars which would most need

[1] § 7, *A*.

this help are the heaviest ones, and their amplitude of pulsation is in fact the largest. It may also be noted that if the direct cause for the variability of Cepheids and long-period variables is in fact different, there is probably a better chance of explaining the well-known difference of phase that distinguishes the two classes.

vi) *Corrections to the analysis.*—If it should prove that neither pulsations nor systematic changes in the model can bring the central temperatures up enough in the very diffuse stars, there might still remain another way out of the difficulty. It is possible, though perhaps not very probable, that the derivation of (3) and (4) is still seriously at fault.

Gamow's formula was obtained by the "Jeffreys method" of integration, and its application in the paper of Atkinson and Houtermans was put in a form independent of the shape of the potential function inside the nucleus (which is permissible if the nuclear radius is small). It is possible, however, that the function has a shape which is not suitable for treatment by the Jeffreys method, and also that the radius at which the potential is a maximum is too large for the generalization of Atkinson and Houtermans. A more accurate treatment might result, in the first case, and certainly would result, in the second, in appreciably larger values of $\lambda$ for a given temperature and density. Whether it would affect mainly the lightest elements (so as to allow a bigger difference of temperature between giants and main-sequence stars) is uncertain; this would depend on the actual shape of the potential curve in the interiors of the different nuclei concerned. It is at least possible. It should be noted that, since $\alpha$-particles are non-magnetic but probably capable of polarization, while protons are magnetic and may be also incapable of polarization, probes with $\alpha$-particles do not necessarily give an adequate indication of the potential curve for protons. Only fast protons can do this, and laboratory technique has not yet quite reached the point at which they can be applied to this purpose.

Provisionally, then, we may hope that if the most diffuse giants do still provide a serious numerical difficulty, it will disappear when the potential energy in the interior of the smallest atom nuclei is known; it is perhaps not very seriously to the discredit of a theory if

it should prove to have been held up, at its launching, on no more well-charted bar than this.[1]

vii) *The absence of small masses.*—Our theory has not yet given any explanation of the fact that at small masses only main-sequence stars occur. This fact has been one of the principal reasons that have led investigators to prefer annihilation theories of matter to transformation theories; if all stars were initially formed with fairly large masses, then it is credible that they should all have settled down into a main-sequence type before they became so old that their masses were small. Russell's theory overcame the difficulty, but the most usual view seems to have been that if stars began their existence at all masses (and on all transmutation theories they must have done so), we should expect small stars to be just as capable of a diffuse existence as large ones, and to be capable of it for a longer time.

Our theory cannot follow Russell here; we really have no reason for saying that a small star could not exist on the beryllium cycle, i.e., in a diffuse state, if it found itself there. But we have an alternative explanation, which it would have appeared somewhat fantastic to suggest on any previous view, but which emerges quite automatically from the position we have been developing; the stars do not now approach their (relatively) permanent state from the direction of large radii but from the other side. Owing to the initial contraction which is necessary at all masses, before a large store of helium-producing nuclei can be obtained, our problem is not to explain how the stars of small mass skip the condition of large radius, but how those of large mass skip that of small radius. This appears comparatively easy.

We have seen that the recovery from the initial compression may be greatly overdone and could perhaps assume the form of an explosion. Even if it did not, if a large amount of long-lived unstable nuclei were formed before the expansion had proceeded far, the resultant generation of helium would involve a continued expansion

[1] In view of Wilson's work (Part I, p. 257, n. 1) this may be extended to cover all stars and all atoms; Wilson's numerical results are somewhat dependent on assumptions about the potential function in nuclei in general. It seems unlikely, however, that the temperatures can be changed much more; the mountain must probably come to Mahomet.

which could reach the same final result slowly. The exact development cannot be predicted until we know the probabilities of formation, and of decay, of the various unstable atoms that would play the chief part, but we can make one qualitative statement.

The violence of the rebound from compression will depend on the amount of excess contraction beyond the main-sequence temperature. A star which can contract very slowly will have the synthesis of helium-producing elements well under way before its radius has become very small, while one that has to hurry its contraction will carry it farther before synthesis is supplying all its needs; as soon as this happens, however, it will rebound more violently than the other because, although the number of syntheses per second is limited in both by the rate of production of helium, the process leads to new helium sources much sooner in the case of the denser hotter star. Thus we shall expect to find the majority of the diffuse stars grouped round that mass at which the original Kelvin contraction was most hurried, since it is here that the rate of doubling of the *He* sources at and after minimum will be the most rapid.

The mass-luminosity law, which, according to Eddington, would hold also for a Kelvin contraction (if we disregard changes in the molecular weight), shows us that the energy radiated per second varies approximately as the third to fourth power of the mass when this is small, and as less than the square of the mass when this is large. The energy developed by a given contraction goes as the square of the mass throughout (or rather less at high masses if we include the effect of radiation pressure). Thus among the light stars the lightest will be able to perform any given contraction at the slowest rate, and among the heavy stars the heaviest ones; in between, approximately where

$$\frac{d(\log \cdot L)}{d(\log \cdot M)} = 2 ,$$

will come those which are compelled to hurry their Kelvin contraction the most. In point of fact the mass at which

$$\frac{d(\log \cdot L)}{d(\log \cdot M)} = 2 ,$$

is about $3\odot - 5\odot$,[1] which is exactly where the great majority of the diffuse giants occur.

Actually, we shall certainly expect stars of any mass above this to be capable of explosion if these stars are; for the larger ones have an appreciably smaller contraction to perform than the smaller ones, in order to reach a given central temperature (or density); they will thus all have a brief Kelvin stage. While therefore we do not know a priori how probable explosion is, we can say that below $M = 2\odot$ the probability will be falling off very rapidly indeed, since the exponent of the $M$–$L$ relation is rising rapidly here, and in addition the radius for an assigned central temperature is falling. Qualitatively there seems no reason to suppose that this may not be an adequate explanation of the fact that giants are very rare below $M = 2.5\odot$, and common above it.

viii) *Constitution of the giants: R and N stars.*—The question of the constitution of the giants presents relatively little opportunity for definite comparison between theory and experiment. Russell's view, that hydrogen must be very abundant in the red giants, is in agreement with our requirements, but his statement that its amount, compared with those of the metals, must be "hundreds of times greater than in the sun" cannot be interpreted to mean that the amounts of all elements other than hydrogen are to be less than 1 per cent of the total; if they were, the stars could spend less than 1 per cent of their total lifetimes in this stage, even omitting the fact that a very considerable amount of synthesis will have been necessary in order to bring them up from maximum compression. Russell's position can be reconciled with the calculations we have already made for the giants if we assume that the elements generated during the giant stage do not manifest themselves spectroscopically.

For helium, beryllium, and boron, a manifestation is in any case scarcely to be expected, since the spectroscopic relationships are unsuitable. For *Li* the same is true with the one exception of the red line at 6708 A. If it were not for this line (which may be slightly stronger in red giants than in dwarfs, but is not much stronger) we could make almost any assumption in reason about the amounts

[1] Slope obtained from an empirical curve fitted to Eddington's figure (*op. cit.*, p. 153). His theoretical curve places the critical mass a little higher.

of all these elements, and a check would be difficult; as it is, we shall have to go into the question further. But clearly in any case there would be no immediate way of distinguishing on spectroscopic grounds between a star with 99 per cent and more of hydrogen, together with a trace of the usual metals, and a star (to take a simple case) with 59 per cent and more of hydrogen, 30 per cent of beryllium, 10 per cent of helium, and a slightly smaller trace of metals; the visible spectra would show the metal lines and hydrogen, and practically nothing else, in both cases, and only refined calculation could hope to decide between the two.

On observational grounds we have apparently to regard the great majority of the lines by which the spectra of giants are judged as being due to "hardly more than a smell of the metallic vapors"—to use Russell's phrase. On the basis of our theory we also expect that the elements above *Be* should probably all be scarce by comparison with main-sequence proportions (though this need not hold for those above zinc); only those atoms are present whose formation occurred during the last stages of the initial compression and the first part of the following expansion. It is easily seen that little detailed comparison is then possible, since the proportions in which these traces should be generated during the "explosion" are almost entirely unpredictable.

Broadly, however, it is undeniable that the observations lead to an unwelcome result. They indicate an extraordinary degree of similarity between the constitutions of a number of bright giants, of various types, and that of the sun. A considerable degree of similarity has been accepted for some time, but it is surprising how complete it seems to be. Professor Russell very kindly showed me some unpublished results obtained in continuance of the paper of Adams and Russell[1] on this point; the elements primarily examined are *Na*, *Mg*, *Ca*, *Sc*, *Ti*, *V*, *Cr*, *Mn*, *Fe*, *Ba*, and *Y*, and while the *Ca–Sc* difference is usually somewhat less marked than in the sun, and the *V–Cr* ratio is also sometimes a little altered, there is on the whole a very marked parallelism, more so than in the original paper.[2]

It is true that there is no particular reason to regard this distribu-

[1] *Astrophysical Journal*, **68**, 9, 1928.

[2] Cf. also Miss Payne, *The Stars of High Luminosity* (Harvard Monographs, 1930).

tion (or, indeed, any other in reason) as intrinsically improbable in giants; there is enough hydrogen for our theory, and the very light elements appear to offer no difficulty (cf. pp. 324, 327). Nevertheless it is disconcerting, and may indicate a fundamental defect in the entire theory, that the distribution should coincide so closely with that which was accounted for in some approach to detail, in main-sequence stars, by a method which cannot be applicable here.

We can merely point out that these heavy stars, which are the ones that overdid the initial contraction the most, and which have since rebounded almost to infinite dilution from the energy point of view, must have used up many times as much hydrogen as the sun in synthesis at this stage. The permanent gases and light metals are those which might be expected to be the commonest survivors of the process, since they have the longest average lives. But the position is not satisfactory.

The possibility should not of course be lost sight of that the sun itself may not be quite a fair sample of a star of the main sequence. It has a planetary system, and was presumably very violently disturbed at a date not earlier than that of its initial expansion (since the heavy elements are present on the earth); and this disturbance probably was accompanied by a considerable amount of synthesis. However, we have not had to assume any trace of this in discussing the sun, so that probably it is practically of normal constitution.

In one respect, however, observation does already indicate an apparent difference of constitution, and it is perhaps significant that it is at a point where our theory can readily admit such a difference, though it does not actually demand it as yet. The division of the coolest giants into R and N types, on the one hand, and K and M types, on the other, seems definitely to indicate a difference of constitution; according to R. H. Curtiss[1] the K and M stars have an oxydizing atmosphere, and the R and N stars a reducing one due to a relatively much greater amount of carbon than usual. Now if a star's central temperature permitted the synthesis of carbon, but was not high enough for oxygen to be reached, carbon would in fact accumulate; a star might in fact spend a fairly long time in such a stage if some radioactive substance had been produced in large

[1] Russell, Dugan, and Stewart, *op. cit.*, p. 865.

amounts during the early expansion process. More plausibly, since it is difficult to see how the radius could otherwise increase, after the creation of the carbon, to a point at which the carbon began to show, the carbon itself was produced in excess during the expansion. It is not difficult to suppose that the conditions during this quasi-explosion should vary somewhat from star to star, so that in some cases the *C–N–O* synthesis could occur and in other cases not. If anything, we might expect the carbon stars to have expanded the more rapidly, i.e., to have the larger masses, but this is uncertain. Incidentally, the possibility that there should be a group of giants with nitrogen the most common element might be worth investigating (though nitrogen has, of course, an odd atomic number); they might appear as R stars with the *CN* bands unusually strong in comparison with the $C_2$ ones.

In red dwarfs, on the other hand, the central temperature is on our view necessarily large enough now to convert carbon to oxygen, so that unless the maximum of the curve in Figure 2 could move to the left far enough to make carbon for this reason more abundant than oxygen, no N or R dwarfs should be found, but only M ones. At the lowest temperatures all classes are of course hard to see, but at least no R or N dwarfs are known, and a number of "late" M ones.

However, we have still to account for the weakness of lithium, more especially in the spectra of those stars in which the *He–Li* synthesis is the only one occurring. Even though only one line is probably concerned, we cannot escape from the conclusion that the proportion of *Li* in the atmospheres of these stars is quite different from what we should expect. It seems by no means improbable, however, that its absence may be due simply to its failure to get up to the surface in time.

We have been working on the assumption that stars are well mixed, and this is only possible if there is an appreciable amount of convection and turbulence in them. We shall see later that there is a good reason, in the case of the main sequence, to expect such turbulence, and it is of course observed in the outer layers of the sun. But this reason will be seen to be almost absent in the giants, particularly in those in which not even the *Li–Be* synthesis is occur-

ring.[1] In that case, $10^8$ years is probably an entirely inadequate time for elements formed at the star's center to work their way to the surface, so that the constitution of their atmospheres should be much as it was at the end of the initial expansion (which was probably turbulent), except that the amount of helium may since have increased. Helium may indeed be very common in diffuse red giants.

### D. THE WHITE DWARFS AND THE NUCLEI OF PLANETARY NEBULAE

It cannot be disputed that white dwarfs have high densities, and they probably have also very high central temperatures. The only possible way that our theory can be reconciled with their existence seems to be by the assumption that where the temperature is high hydrogen is entirely absent; it is therefore satisfactory that this state of affairs should in fact develop when hydrogen begins to be scarce in the star as a whole.

Rosseland has shown[2] that the radial electrostatic field which will clearly be set up by diffusion outward of the free electrons may in fact be quantitatively sufficient to drive the hydrogen (which is most easily affected) from the center of the star and concentrate it toward the surface. In a star consisting of 50 per cent of hydrogen by volume the effect would not be very great, but a comparatively short further existence will suffice to make it so. If, for example, the most abundant other element is oxygen, such a star has used up sixteen-seventeenths of all its hydrogen by weight, and is therefore relatively old; from this point onward the percentage change in the amount of hydrogen will obviously rise somewhat rapidly, and the conditions of Rosseland's theory might soon become realized.

White dwarfs would represent in that case stars which have consumed nearly all their hydrogen, although their external appearance might not suggest it. As the hydrogen leaves the center, the energy generation will cease there, and there will be nothing to oppose contraction except the heat which it develops. They will therefore contract away from the main sequence rapidly at first, but as their radius diminishes the efficiency of the gravitational process

[1] Other causes may, of course, still be operative. Cf. Eddington, *op. cit.*, pp. 282–288 and references there.

[2] *Monthly Notices of the Royal Astronomical Society*, **84**, 720, 1924.

increases, and their change of radius will slow down. Since in addition stars with heavy centers radiate less than ordinary stars of the same mass, gravitational energy will be less urgently called on when they have become small, and a relatively permanent state is thus possible even if there is no subatomic energy source at all now.

It is of course conceivable that at the temperatures reached other sources of energy might come into action. Synthesis from carbon to xenon in $\alpha$-particle steps would provide a little energy, if there were any helium left; otherwise nothing appears very probable unless the annihilation of matter could occur. In the present state of our knowledge of this subject it is easier to estimate the minimum temperature that would influence such a process if it occurred than to say whether the process is possible at all. Estimates of this sort seem, however, to be somewhat liable to revision by the wave-mechanics in any case.

Qualitatively there would seem to be little real need to call on such sources, at least if the total life of the rest of the universe is about what we have supposed. A star in which the red shift ought to appear (according to the general theory of relativity) is one such that an appreciable proportion of its original mass has been turned into radiation by gravitational contraction alone; gravitational energy can then presumably compete on roughly equal terms in such a case with the energy which (according to the special theory) may be set free by the more familiar mass change found in synthesis.[1] Calculation shows in fact that the gravitational energy lost by the white dwarfs is enough to supply their present rate of radiation for about $10^{11}$ years; this figure is obtained, however, from a formula which does not include the effects of gas degeneracy.

We should expect a "stellar graveyard" to contain the relics of a large number of O, B, and A stars, as well as of those of smaller mass; their spectra must almost certainly be of type O or hotter. The heavier stars are of course scarcer, but they die sooner; if even in the very dense state they radiate (as we should expect) more than

[1] Gravitational energy is comparable with that obtainable from synthesis when $GM^2/R$ is approaching comparability with $Mc^2$; the red shift is appreciable when $GM/Rc^2$ is approaching comparability with 1. The modification of this statement to take account of gas degeneracy might involve a far-reaching fusion of the quantum theory with general relativity.

the ordinary white dwarfs, they will also be visible farther, though of course high radiation will cut short this phase too. But we should expect to see some at least. Now it appears in fact that there are quite a number of O stars of very much fainter magnitude than the normal figure $(-4)$; they are usually the centers of planetary nebulae, but if we omit that fact for the moment their number and galactic concentration are suitable. We may therefore predict a very high density for these stars also, and include them generically with the white dwarfs.[1] The planetary nebula that normally accompanies them may appear here and not in the ordinary O stars as a result of the difference in constitution, though this is speculative. It may also be due to a higher surface temperature. This explanation of these stars is not bound up with the present theory; if correct, it does involve, however, that even heavy stars can "die," i.e., it involves the short time-scale.

## 7. STABILITY

### A. OVERSTABILITY AND THE DELAY FACTOR

It is well known that for a star to be stable energy generation must be stimulated by contraction, and this condition is of course satisfied by our theory. But according to Eddington the stimulation could easily be so great that the star would overcorrect any slight departure from equilibrium, so that an infinitesimal disturbance would result in oscillations whose amplitude would increase rather than die out. Eddington calls this condition "overstability,"[2] and shows that it is to be expected if the energy generation varies with more than the square of the temperature. He himself inclines, however, to the view that the rate of variation does depend very extremely on the temperature, approaching, in fact, a discontinuous function rising abruptly at a critical temperature; in order to prevent overstability he assumes that while the processes that generate

[1] NOTE ADDED JUNE 4.—When this was written, I was not aware that Jeans had already made the same suggestion, although for a different purpose (*The Universe around Us*, p. 309). The idea seems to have been first proposed by Menzel (*Publications of the Astronomical Society of the Pacific*, **38**, 302, 1926), whose reasons were observational. Cf. also Russell and Atkinson, *Nature*, May 2, and a correction (in print); Gerasimovič, *Observatory*, April; Milne, *ibid.*, May. Other additions to the "white dwarfs" now seem probable among the B stars; cf. Bottlinger, *Zeitschrift für Astrophysik* **2**, 151, 1931.

[2] *Op. cit.*, pp. 200 ff., 299, 304.

the energy depend very greatly on the temperature, the actual emission of the energy is delayed, after such processes have occurred, for a time between a few months and a thousand years; he suggests that this time should be independent of external conditions, but this does not seem essential.

Our theory clearly has the very rapid rise of energy generation that Eddington (and others) had been led to postulate, and even succeeds in reproducing his "delay factor" more or less faithfully. It appears, however, that there are several influences here, and perhaps the most potent one is of a somewhat different nature than that contemplated by him.

The amount of helium near the center of a main-sequence star must be very small. If a proton that penetrates a *He* nucleus always remains inside (and the difficulty with the giant stars is increased if it does not), the average life of a helium nucleus is only half a second ($\log \lambda = 0.3$) in the sun; and since about $10^{8.5}$ *He* nuclei must disappear per second per cubic centimeter there will be only about $10^{8}$ of them present per cubic centimeter. Obviously, their instantaneous conversion to *Li* will only produce a fraction of half a second's supply of energy, as compared with the millions of years' supply actually present in the form of temperature energy. The *He–Li* synthesis is thus not in itself a serious source of danger.

The lifetime of *He*, and even of *Li*, is in fact so short that the liberation of a *He* nucleus near a star's center may be regarded as equivalent, for all practical purposes, to the immediate generation of energy. To this extent Eddington's delay factor is exactly reproduced in our theory, since the formation of the radioactive atoms depends on the temperature but their disintegration presumably does not. But it must not be forgotten that all syntheses develop energy, and roughly each one of the sixteen steps from $He^4$ to $O^{16}$ and $Fe^{56}$ to $Zn^{60}$ is responsible for an equal amount of energy per second, whether the actual amounts of the elements involved are large or small. In fact, the *He–Li* step liberates less than the usual amount, since the *Li* nucleus is abnormally heavy. Thus the effect of the delay factor might easily be inadequate, since it is operative only for a small fraction of the energy supply. In addition, if the average life of $Zn^{60}$ is fairly long (as we must probably suppose it to be), the fluctuations in its absolute amount will be small even

in a pulsating star, and the supply of helium will be practically constant. On recovering from a temporary expansion a star will thus find more helium than the normal amount waiting for synthesis, and will probably rebound with greater violence again.

There is, however, the following further guaranty of stability, which is perhaps more powerful. The rate of energy generation for all the lighter elements varies, as we have seen, approximately as $T^{\xi^2}$, and $\xi$ varies as $Z^{1/3}$. Thus a temporary compression affects *Li* more than *He*, *Be* more than *Li*, and so on up to nitrogen. The following expansion practically halts things, and holds them "frozen" until the temperature rises again. When this happens, i.e., when the star collapses once more, it will therefore find all those elements whose synthesis times are longer than the pulsation period somewhat depleted; before it can get back to its normal state it will have to "save up" in every one of the departments affected. The temporary shortages will be recovered from at rates incommensurable with each other and unrelated to the pulsation period, which appears to make the maintenance of pulsations quite improbable. In effect, a star that begins to show signs of "flightiness" will thus automatically be put on a reducing diet until it has steadied down again.

This argument is of course not rigorous as it stands; in general, however, it seems likely that any very complicated process of energy generation will be less likely to lead to maintained oscillations than a simple one would. The present theory is simple in its physical assumptions, but leads to a decidedly more complicated situation, as far as the actual energy generation under stellar conditions is concerned, than any previous ones. The rate of generation depends not merely on temperature and density, but on the time these temperatures and densities have lasted and the values that preceded them. It is probably not too much to claim that the danger of "overstability" is at least not now immediately evident.

The argument applies of course only to the main sequence. Giants have clearly less guaranty against oscillations; and very diffuse ones, in which the helium must be supposed abundant and only the low temperature prevents its immediate conversion to lithium, have no guaranty at all. It is thus significant that, with the exception of the cluster variables (and one or two apparently related stars), for which

we have already suggested Eddington's explanation, no main-sequence stars seem to be variable; there are of course eclipsing binaries, and there are some dwarfs in the Orion region that are believed to be intermittently dimmed by dark nebulae, but there is no intrinsic variation.

### B. THE HELIUM PROBLEM

The very small value we have calculated for the amount of helium at the center of a star is in marked and, at first sight, extremely disconcerting opposition to Russell's observational estimate. His figure is uncertain, but can scarcely be $10^4$ times too large even though helium seems to behave anomalously, from the spectroscopic standpoint, in the sun and also in other classes of stars. (There are, for example, stars with helium lines stronger than one might expect if their atmospheres consisted of nothing but helium.) Even a factor of $10^4$ would not be nearly enough to bring Russell's figure down to ours, and unless then we can show that the helium is probably confined to the surface the whole theory is endangered.

It is not, for example, practicable to assume that the *He–Li* step is exceptionally difficult, as would be the case if the proton that penetrated the $He^4$ nucleus usually failed to remain there; giant stars would not in that case have any source of energy at all. The assumption that high temperatures would often cause the proton to be expelled again, while low ones would not, has also been tried and found very difficult. But there is a fair amount of ground for the view that helium could be much more plentiful at a star's surface than in its interior.

Helium is exceptional in that it can be produced in any part of a star, not merely in those where synthesis is occurring. If there is even a very little mixing, as we have supposed, and if there are radioactive elements of long life, as we have also assumed (and as is practically certain in any case), then radioactive atoms will be found in the outermost layers, and helium will be produced there. It will not be destroyed, however, in appreciable amounts at temperatures below, say, 1,000,000°, and it must therefore work its way in for perhaps one-third of the stellar radius before it gets into danger. Diffusion alone would require a long time to bring it so far; mixing currents are of course more effective, but we do not know how much more.

If, as the sun-spots indicate, there is a very actively mixed layer for some distance below the surface, the distance that both the radioactive atoms and the helium atoms have to travel without much help is of course reduced. But quantitatively there is a problem here, whatever rate of mixing we assume, since whether the mixing is rapid or slow a high concentration of the radioactive atoms would seem to be necessary at one end of the line if there is to be a high concentration of helium at the other. Almost certainly there will not be a high enough concentration of any radioactive substance for our purpose. We must therefore turn to the question of selective effects, both in diffusion and in streaming, and inquire whether these can help us—in fact, it seems probable.

### C. DIFFUSION AND MIXING

There will be an appreciable range of temperatures within which helium is completely ionized and all heavier atoms retain both, or at least one, of their $K$-electrons. In all this region helium will be urged outward by the electric field more than any other element except hydrogen. In regions, therefore, in which there is no pronounced streaming, helium, and to a less extent the immediately following elements, may actually exhibit a preferential outward motion.

The fact that the same is roughly true for *Li*, *Be*, etc., is perhaps important because $Be^8$ can be formed quite far from the center in main-sequence stars, and will add to the surface helium if it moves outward. (It cannot of course be formed quite as far out as helium can be destroyed, so that unless it moves a considerable distance before disintegrating it will not help. In $10^{8.5}$ years, however, it might well be urged some distance.)

This selective effect is somewhat discounted by the fact that hydrogen is much more subject to it than even helium, and most of the atoms are hydrogen. It will also not be noticeable if streaming is the more important mixing factor.

As regards streaming, we may note that any mass of material that contains an unusually large amount of radioactive substance will be urged upward as long as the temperature is above about $10^{6.5}$ degrees. For helium will be produced more rapidly in this mass than in neighboring ones, and the resulting generation of energy will heat

the mass. This will be true at all points from the center outward for about two-thirds of the radius. The mass may of course cool intermittently if it expands too rapidly in its ascent; it will, however, resume its journey upward with a temporarily increased proportion of helium due to the pause in synthesis, as soon as radiation has warmed it again.

If we imagine such a mass of gas to start near the center and to rise steadily, a point will be reached where the $Be^8$ in it can no longer be converted to *B;* but there will still be some distance to go before the *He* that is being produced stops being fairly rapidly converted through *Li* to $Be^8$; thus the total amount of long-lived radioactive matter may even increase in the mass during this stage. Farther out again, although $Be^8$ can now no longer be formed, the *He–Li* synthesis will continue to supply energy and keep the mass moving outward.

In the absence of any other deep-seated cause for upward currents this might be an explanation for sun-spots.[1] It would perhaps be rash to use it also as an explanation of the preferential appearance of helium in and near these spots, difficult though that is to account for otherwise, but at least it seems a fair reason for expecting a moderately rapid supply of helium to the outer layers in general. The question whether the apparent amount of helium in the chromosphere changes as between sun-spot maximum and minimum might be worth investigating. The long life assumed for $Be^8$ is awkward to fit into this explanation; possibly we must rely on other unstable elements ($Zn^{60}$, etc.).

It may be noted that upward currents of this nature are scarcely likely to form in very diffuse giants, since there is only one region, near the center, where helium can be destroyed (cf. p. 327).

Even with a rapid supply in the outer layers, helium will not accumulate to a marked excess if it can also be rapidly removed from them. Probably, however, this does not occur. There seems little chance of a mechanism that would cause comparatively narrow

[1] A. Unsöld (*Zeitschrift für Astrophysik*, 1, 138, 1930) has shown quantitatively that recombination of hydrogen ions can achieve the same effect in a layer of appreciable thickness nearer to the photosphere; his process could carry on out to the surface a streaming motion started by the present one.

columns of gas to descend fast, and the uprush of the sun-spots is probably compensated by a very general, almost uniform, sinking of the remaining regions. In that case the selective effect of the electrostatic field might retard the helium somewhat by comparison with the other atoms. Farther down, where synthesis begins to be possible, it is obvious that if any region contains more helium than its neighbor it will be buoyed up by the heating effect. None the less, the whole problem is one that is too complicated for adequate treatment here, and there may be a considerable amount of difficulty still to be disposed of.

It may be noted that the effect of these upward currents will be to decrease the inequalities in the amounts of the lightest elements, so that they will vary appreciably less than according to (3) and (4). In an upward current first oxygen, then nitrogen, then carbon, and so on gradually stop being formed, and the relative amounts of *Li* and *Be* will be larger than when the current started. This is satisfactory, since the change in the figure for the central temperature, from the 40,000,000° on which Table I was based to the 16,000,000° calculated in the present paper, together with the change from formula (1) to formula (3), considerably increases the differences between successive elements, and they were already somewhat too large for the observational values even in Table I. *Li*, for example, seems to be slightly more abundant than *Be*, instead of much less.

When laboratory technique has advanced to the point at which synthesis of these elements can be attempted, and if synthesis should then in fact be observed and its probability definitely measured, it seems not unlikely that the relative amounts of the lightest elements in the sun's atmosphere might give us better information about the amount of stirring at great depths than any other method known at present.

If we may take it that helium extends to a fair depth in a star before it begins to become scarce, it is clear that the impact of a mass of meteoric matter,[1] which could easily penetrate some distance, might result in an explosion sufficient to cause the phenomenon of a nova. The stellar material toward the outside of a star is

[1] Suggested by Seeliger and Pickering; cf. Russell, Dugan, and Stewart, *op. cit.*, p. 922.

richer in more immediately "explosive" components (helium) than the center, and no extremely high temperatures would seem to be necessary. Since we have not, as a rule, any certainty of being able to see such matter, if it were to be traveling through the solar system, it appears that the human race may be "living on the slopes of a volcano" with somewhat less security of tenure than is usually taken for granted.

## 8. COMPARISON WITH PREVIOUS THEORIES

### A. ARGUMENTS IN FAVOR OF A LONG TIME-SCALE

i) *Binaries.*—Of the various arguments in favor of total annihilation of matter, as opposed to transmutation, perhaps the strongest is that due to Jeans.[1] He showed that the eccentricities of the orbits of binaries increase with increasing separation in a way that would occur as a result of random collisions if a very long time-scale were permissible; it is, in fact, difficult to obtain a long enough time even if destruction of matter is the main source of stellar energy, and with transmutation it is prima facie out of the question.

If, however, the galaxy has been expanding throughout its history, and Jeans inclines in any case to the view that it has, the position may be appreciably different. Collisions would have been much more frequent in the early history of the system than now, if the expansion were considerable, and it might be possible to reconcile Jeans's theory of the distribution of eccentricities with even a short time-scale.

General relativity leads of course to the view that space as a whole, in which are imbedded the extra-galactic systems, is expanding, and the motion is also observed, as is well known. It would be rash to transfer the argument without alteration to the case of a single galaxy, since the minor irregularities, in the space density of matter, that we know as galaxies are neglected in the theory at present; if, however, we venture this step we find that the galaxy may have been quite small $10^{11}$ years ago.

The present velocity of distant nebulae is at the rate of 500 km/sec. for every million parsecs distance. If the galaxy is 10,000 parsecs across, its outer boundary should be expanding now at about

[1] *Monthly Notices of the Royal Astronomical Society*, **77**, 186, 1916.

5 km/sec., or its radius should be growing according to the equation $dR/dt = \lambda R$, with $\lambda = 10^{-16.8}$/sec. This means a doubling of the radius about every $10^{9.1}$ years, if the rate were constant, which is very much more than we should require. The whole argument is of course very speculative at present, and possibly the calculation cannot be put in this form in any case; but it is perhaps fair to regard the question of the time-scale as not necessarily settled yet by the argument from binaries.

ii) *Spread of clusters.*—There is evidence that in close globular clusters most of the stars are fairly massive; stars of the sun's mass, for example, seem to be less common than in the galaxy as a whole. In more open clusters smaller masses are more common. According to Jeans a cluster that began as a "close" one would tend to spread, owing to interactions with other systems, and if the stars in the open cluster are to be regarded as older it is natural, though not necessary, to attribute their smaller mass to their age.

There seems, however, no real objection to the view that where the original concentration of hydrogen was high, large stars close together might be formed, and where it was low, smaller stars farther apart.

It is also very difficult to see what the early history of the close clusters can have been on this view. If their stars cannot be more than, say, $10^{12}$ years old, and small dwarfs can easily be (and by hypothesis in this argument are) perhaps $10^{14}$ years old, the close clusters must either have sprung into existence, by actual creation of matter, quite late by comparison with other stars, or else the first 99 per cent of their life must have been in some non-stellar form. It must be admitted, however, that this difficulty, with altered numbers, is not entirely absent from the present theory either.

iii) *Stellar masses in general.*—If the mass-luminosity law is used to make a tabulation of the relative numbers of stars of different masses throughout the galaxy, it is of course found that the numbers rise with decreasing mass. This would be expected if the universe were a collection of stars of all ages, and if the various lifetimes were those calculated from the annihilation theory; over a limited range of magnitudes the figures are more or less in quantitative agreement. They would not be very greatly different, however, in this

range if the lifetimes were those calculated from the transmutation theory; and the extreme differences of age, over the whole range, required by the former theory are on the whole somewhat difficult to accept. On our theory no stars have a minimum age except that calculated for a Kelvin contraction (which may matter for very small dwarfs, especially the massive white dwarfs), and we do not actually suppose that any of them approach $10^{13}$ years in age even though the hydrogen supply of small dwarfs would allow such a figure ultimately.

We have no definite theory to explain why there are not more very massive stars; but they cannot of course remain bright very long, and the number of them may have been larger when the galaxy was younger. Also the high percentage of binaries among the B stars suggests that on the average angular momentum may militate against the possibility of very heavy stars.

iv) *The gap among the M stars: critical radiation pressure.*—The fact that no M stars of absolute magnitudes between 2 and 6 are known has been regarded as indicating that no stars are formed with masses small enough to have these magnitudes when they first contract enough to become visible. Eddington sought to justify this limitation by an argument based on the ratio of radiation pressure to gas pressure in stars of different masses; stars should be unable to form (or remain formed) if they were so large that the radiation pressure was overwhelming, but should form and continue to grow (presumably by accretion) up to this point.

The theory that a star would tend to break into two if its radiation pressure were extremely high seems open to serious objection, however; and in any case the revised constitution of the stars based on Russell's hydrogen figures appreciably reduces the rôle that radiation pressure can be supposed to play. Moreover, it was always somewhat doubtful why no star should form at a mass comparable with the sun's, supposing that it found no further diffuse matter within reach after it had grown to this size; the argument actually imposed only an upper limit, not a lower one.

On our view, although of course $1-\beta$ must not be very small by comparison with 1, the fact that radiation pressure is becoming perhaps quite as large as gas pressure in the (heavy) stars must

probably be regarded as an accident, with no special significance. The high absolute value of the radiation density may be a vital factor, however, in the possibility of occurrence of process B.

v) *Exhaustion of the energy supply.*—Eddington assumed that since the figures he obtained for the central temperatures were nearly constant throughout the main sequence, the great differences in energy generation per gram observed there could not be due to temperature. He therefore postulated that they must be due to exhaustion of the active material.[1] This is easily seen to demand a long time-scale, since it is incompatible with an approximate permanence of stellar masses unless the stars are to be scattered widely on the Russell-Hertzsprung diagram, so that there would be, after all, no main sequence from which to argue. The variation of the probability of synthesis with temperature is so great, however, in our theory that even Eddington's figures show enough systematic change to cover the facts, and Jeans's modification of the theory also makes a much smaller dependence on temperature permissible, as far as the main sequence is concerned.

### B. ARGUMENTS FOR THE SHORT TIME-SCALE

i) *Open clusters.*—There are many systems, such as the Taurus cluster, which must almost certainly be regarded as single units having a common origin, in which nevertheless giants and quite small dwarfs are mixed. Since it is almost impossible to suppose that these systems have existed ten or a hundred times as long as the giants in them can have existed, it becomes necessary in these cases to suppose that the dwarfs are, after all, young. If so, other dwarfs may be young also; and there is no longer any explanation of the fact that not even in these clusters are diffuse dwarfs found, except of course that given by Russell's theory, which does not demand a long time-scale, and, indeed, in this case cannot admit it either.

ii) *Diffuse interstellar matter.*—Eddington has recently shown[2] that the presence of interstellar material is difficult to reconcile with a very long time-scale, since its mere viscosity would have checked the galactic rotation if this has existed many times as long as $10^{10}$

[1] *Op. cit.*, pp. 298–299.

[2] *Nature*, **127**, 177, 1931.

years. This argument appears to share with that of the foregoing section the property of being more direct and difficult to evade than most of the considerations that have been urged in support of one time-scale or the other, at least unless the galaxy is not expanding.

On the whole, then, it appears that the short time-scale provides fewer serious difficulties (none, with an expanding galaxy) than the long one, so that even if no direct arguments in favor of transmutation, as opposed to annihilation, were yet known, it would seem to be the more probable theory.

### C. OTHER DIFFICULTIES

i) *"Impossibility" of the formation of helium: the temperature problem.*—Among the points that have previously been urged against the idea of transmutation of the elements, the fact that the *H–He* synthesis seemed the most fundamental and was clearly extraordinarily difficult has always been prominent. This is of course disposed of by the present theory, as it was in that of Atkinson and Houtermans; six-body collisions are now as unnecessary as they are unwelcome.

It has also been urged, even recently, that very high temperatures are essential for any form of energy generation, and that 40,000,000° must "on thermodynamical grounds" be quite inadequate. As to this, the equations are there; the greater part of the energy in main-sequence stars, and all of it in giants (though they are colder still), is developed in our theory by process A, which follows from the wave-mechanics with some plausibility. Process B is admittedly an *ad hoc* assumption, but if process A is admitted process B cannot be ruled out merely on grounds of temperature.

Some difficulty has also been felt a priori in the idea that the probability of energy generation should vary very rapidly with temperature. Process A shows that the difficulty is in fact illusory, but this is not a consequence of the wave-mechanics; it is a consequence of the classical Maxwell formula. The number of protons with speeds of $10^{7.6}$ at temperatures in the neighborhood of $10^{6}$ does vary as about the twentieth power of the temperature, and all the wave-mechanics has done in this respect is to find a use for these protons.

ii) *Heavy elements in diffuse stars: interstellar calcium.*—A specific objection to the idea of synthesis was that presumably diffuse red stars are very young, and yet they show such elements as *Ti*, and even *Zr*, in abundance. Related to this was the question of interstellar calcium; the entire galaxy is permeated with atoms of this element, at very low densities and temperatures.

As to the giants, Russell's results show definitely that at least in their atmospheres (which is what they were judged by) the "abundance" (in terms of the total mass) is pure illusion. And our theory does not merely allow, but actually demands, some generation of heavy elements in the very early history of every star; the initial contraction is not at all a hypothesis, but an almost inescapable consequence of our hypotheses.

The interstellar calcium must probably be supposed to have been "blown off" stars by radiation pressure, as has already been suggested by Eddington. A star whose average velocity is 20 km/sec. could cross the galaxy and return about every $10^9$ years, and it is thus not surprising if the distribution of calcium appears practically uniform. Its amount does not seem difficult either. Whether a similar process can account for the oxygen and nitrogen in diffuse nebulae is perhaps more doubtful.

iii) *Double stars.*—The broad outline of the escape offered by our theory from the "very awkward paradox" of Eddington has already been given. Leonard's analysis[1] shows in fact that though the more luminous star of a pair is often the more diffuse, both stars occur in regions of the diagram where this theory allows an adequate generation of energy, the smaller star being in fact usually in the main sequence. If many pairs existed in which one star was of class B and the other was not only a diffuse giant but was heavier, there would be some difficulty, but pairs of this sort are uncommon.

Moreover, both stars of a pair may be diffuse giants and yet the more luminous (and therefore the more exhausted) one may still be the more diffuse; for the other one may be still expanding. We have obviously gained a great deal of "elbow room" in this respect.

In eclipsing binaries the less luminous star is usually the more diffuse. This, as Shapley has pointed out,[2] is probably largely a

[1] *Loc. cit.* [2] *Princeton Contributions*, No. 3, p. 110.

matter of selection of data; variability is much more readily noticed in such pairs than when the position is reversed. But cases of this sort are at any rate not uncommon. Our theory allows either star to be the diffuse one.

### D. DIFFICULTIES OF PRESENT THEORY

i) *The isotope-question: "missing" atomic weights.*—It remains to note some difficulties inherent in the present theory. Some of them apply equally to all transmutation theories, but the first one is specific for synthesis chains. We have ignored, up to now, the difference between steps in atomic number and steps in atomic weight.

It is true that every atomic weight from 6 to 37 occurs on the earth; but some of them are decidedly scarce, and there is no good ground for supposing they would be more abundant in the sun except in the cases of $Be^8$ and $He^5$. We regard differences in atomic weight as strictly the more fundamental (although the atomic number is what appears in the formula for $\lambda$), since we regard the possible adoption of electrons as comparatively unimportant. In a synthesis chain the atomic weight 15, for example, must be reached sometime, and whether the nucleus is called oxygen, or captures another electron and becomes nitrogen, will have little influence on the question whether the atomic weight 15, taken as a whole, is abundant or scarce.

An abnormal abundance of any one atomic weight may be readily accounted for by the supposition that the next proton to penetrate frequently fails to anchor itself. We may well suppose this is usually the case when the atomic weight is divisible by 4. An abnormal scarcity is more difficult; if succeeding places are once more occupied in equilibrium proportions, not even the argument used for scandium is valid. Thus it appears probable that Figure 2 ought to be redrawn in terms of atomic weights, and a smooth curve ought to be laid, if possible, through all the least abundant ordinates, not through the most abundant. The "equilibrium proportions" would then be represented by a smooth curve departed from in the majority of cases, but always in the same direction. This would be unfortunate, since it would mean (at present) an individual assumption for each one of at least three-quarters of all possible atomic weights; but we

are not really entitled to say that nature will not prove to be as complicated as this.

It would also involve somewhat higher temperatures in the main sequence, since not only temperature but also the small probability of obtaining anchorage would now be keeping most of the constants of synthesis down to their small values. Higher temperatures in the main sequence would be an advantage, however, on the whole, since the difference between them and those of the heavy giants would then be greater.

The difficulty is often not as great as it seems. $O^{17}$ and $O^{18}$ are estimated,[1] for example, to be both commoner on the earth than nitrogen. It probably becomes acute, however, as has already been pointed out, with neon. The mere absence of neon from stellar spectra is not the only difficulty; if the penetration of electrons were easy when $Z = 10$ and very difficult when $Z = 11$, whatever the atomic weight, neon atoms might generally fail to reach the surface of the star without transformation. The trouble is caused by terrestrial neon, sodium, etc., which show us that the atomic weights 20, 21, and 22 are extremely scarce whatever the value of $Z$. It is possible that scarce isotopes of sodium, which is of course abundant, would help us out here, but they are hardly to be expected.

Difficulties of this nature made it seem preferable to develop the theory without any attempt, for the present, to explain the detailed features of the abundance diagram, especially the comparative scarcity of odd $Z$-values. It is obvious that there is still a considerable amount to be done here, but the next step will probably not be taken from the astrophysical side. In process B, of course, it is conceivable that certain steps should be particularly easy. This would remove all difficulty, since even *Ne* is governed mainly by this process.

The apparently complete absence of $Li^5$ and $He^5$ on the earth is not surprising. It appears probable that $He^5$ would be the more stable (since otherwise $Be^6$ must be supposed stable), and this will account for the absence of $Li^5$. And there is nothing to prevent our supposing either that the total amount of helium of both sorts was extremely small in that portion of the sun that finally became the

[1] Harkins and Schuh, *Physical Review*, **35**, 812, 1930.

earth or that during or since the earth's cooling a considerable loss of helium took place. In fact, this last view is almost forced on us, since there is, as Lindemann has pointed out, too little helium in the atmosphere even for the known radioactive minerals. The helium now present can have been formed subsequently; it will obviously all be $He^4$.

ii) *White dwarfs in binaries.*—Where the white dwarf is more massive than its companion, the more rapid exhaustion to which heavy stars are normally subject will account qualitatively for the situation on the assumption of a common age and origin for both stars. In the opposite case the position is difficult. Our theory apparently demands that in such cases either the two stars shall have different origins and ages, or the hydrogen shall have been very unequally shared when the star divided. Assumptions of unequal sharing have frequently been made, to overcome difficulties presented by binaries; but the idea is peculiarly difficult in the case of hydrogen, which must presumably still have been overwhelmingly the most abundant element when the star divided.

It is possible, when the masses do not differ too much, to hold the $R^{-1/2}$ term in Eddington's mass-luminosity formula responsible. If the more massive member were a diffuse giant during a large part of the system's history, it could radiate less than the other, and at a later stage the more prodigal partner would be the first to declare itself bankrupt. It would not even be necessary for the absolute radiation of the larger star to be less; a less radiation per gram would probably suffice. None the less, it is possible that a difficulty remains here.

iii) *Cosmic rays.*—While the wave-lengths of cosmic rays seem to be still subject to some dispute, at least it is generally agreed that there are rays whose energy is comparable with that liberated by the total annihilation of a proton. To ascribe any cosmic rays to synthesis, in a single act, of a very complex nucleus is admittedly difficult in itself, though an agreement in the energy values might force such a step; to ascribe them to annihilation is of course to admit the possibility of annihilation.

Our theory obviously involves the continual emission of nuclear $\gamma$-rays by new-formed elements, but the frequencies must be considerably less than the measured ones; moreover, the emission will

normally occur so deep within a star that nothing would escape to be measured.

An easy, but wasteful, way out of the difficulty may perhaps be to assume that annihilation occurs, but that it is not the main source of stellar energy. Alternatively, we may suppose the Klein-Nishina formula to be wrong; but this is not attractive. If we suppose that single-process complex synthesis does occur, it is natural to imagine that rising density should favor it very greatly indeed, which would cause extreme difficulties; the possibility, however, that what favors it is extremely low temperature may be worth considering, though it would not account for the faint periodicity with solar time recently observed.[1] We should have to imagine minute crystals of solid hydrogen, perhaps with other elements present too, as suddenly coalescing into a single atom. Beyond leading to somewhat less severe difficulties than the alternative view, this has no direct recommendation.

## 9. CONCLUSION

This paper started as hardly more than an academic exercise in the application of the law of mass action and the standard equilibrium theorems of radioactivity theory to stars of constant mass and radiation; consideration of the subject was begun immediately on the appearance of Russell's estimates for the amounts of the lightest elements in the sun, and was prompted at all times by the feeling that the theory of regenerative synthesis opened up a number of new possibilities. The assumption of process B is not the only one that can make the machine work, but it seems to be the simplest one; in a first attack this is important, especially as even so the developments are somewhat intricate. But the amount of success achieved is rather more than was expected.

In fact, it is perhaps fair to claim that the difficulties resolved by the present theory and those introduced or left unresolved by it are on the whole of qualitatively different natures. The position is no longer full of admitted and apparently insuperable contradictions, nor are the fundamental hypotheses to which we must turn all devoid of direct physical support. The difficulties that remain are mostly specific individual ones, such as may be cleared up by further

[1] Hess, *Nature*, **127**, 10, 1931.

knowledge on specific points, and the explanations do not promise to interfere with each other. Moreover, the total number of difficulties has probably been enormously reduced. This is not immediately evident, since a great many points have been dealt with that were not touched by earlier theories; if they had been, however, the difficulties would not have been far to seek.

The amount of arbitrary assumption has not been reduced to zero, but it is small. Process B is not, for example, in spite of its specific nature, more arbitrary than either one of Russell's two processes, both of which were needed to explain stellar types and magnitudes; and taken together these did not of course extend to the question of the abundance of the elements.

To some extent we may claim to have adopted the most successful portions of the theories of Eddington, Jeans, Milne, and Russell, and apparently without serious contradiction. We have taken Eddington's general position, Jeans's modification which takes account of the proper absorption coefficient, and Russell's value for the hydrogen content which makes this admissible (not to mention a great many other matters of theory and of observation); and we have satisfied Milne's condition for stars without heavy centers, namely, that their existence must be due to the form of the relation between temperature and energy development. Where such distinguished investigators differ as much as these do it would be difficult to agree entirely with them all; but at the same time it may perhaps be hoped that they will at least not find themselves united now in opposition to all of the major ideas here put forward.

I am extremely grateful to Professor Russell for an immense amount of kindly criticism, information, and most valuable advice. Whatever clearness of presentation the paper has finally achieved is also due entirely to him.

DEPARTMENT OF PHYSICS
RUTGERS UNIVERSITY
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# THE SPECTRUM OF H.D. 50138[1]

By PAUL W. MERRILL

ABSTRACT

*Bright hydrogen lines* were discovered in this B8 spectrum at Mount Wilson in 1920. Variations in the intensity of one of the bright components of $H\beta$ soon attracted attention. The *forbidden O I lines* at λλ 6300, 6363 are present as emission lines of low intensity.

*Displacements of the lines.*—Since the lines do not all have the same displacement, they must be studied individually. The absorption lines $H\gamma$ and $H\delta$ agree, but the central minimum of $H\beta$ gives an algebraically smaller displacement. λ 4471 *He* and λ 4481 *Mg* give scattering values which have little in common with those of hydrogen and, in the mean, differ widely from them. Behavior of the weak iron lines is intermediate between that of λ 4481 and that of the hydrogen lines. The variations of the hydrogen lines are greater than the errors of measurement, but the shifts appear not to correspond to a simple orbit.

*Structure of the lines.*—$H\beta$ has two strong emission components separated by about 4.2 A. The red component maintains its intensity and position practically without change. The violet component, however, exhibits striking changes in intensity and position which are studied in detail. The bright portions of $H\gamma$ and $H\delta$ are much less intense than those of $H\beta$, but the central absorption is strong and well defined. Lines of helium, magnesium, and iron are wholly dark.

*Discussion.*—The changes in the intensity of the violet emission component of $H\beta$ cannot be caused by hydrogen absorption of the same type as that which produces the central dark lines of the Balmer series. Explanation by the occultation of the approaching limb of a rotating star is too artificial to be convincing. Among numerous puzzling features is the failure of the bright hydrogen lines to shift with the absorption centers. The behavior of the hydrogen lines in H.D. 50138 presents a remarkable similarity to that observed by Joy in the companion to *o* Ceti (Mira).

Bright hydrogen lines were discovered in the spectrum of this star[2] on plates taken by Mr. Humason and the writer on Mount Wilson in December, 1920.[3] On later photographs interesting variations in the structure of the bright $H\beta$ line attracted attention and led to the present investigation.

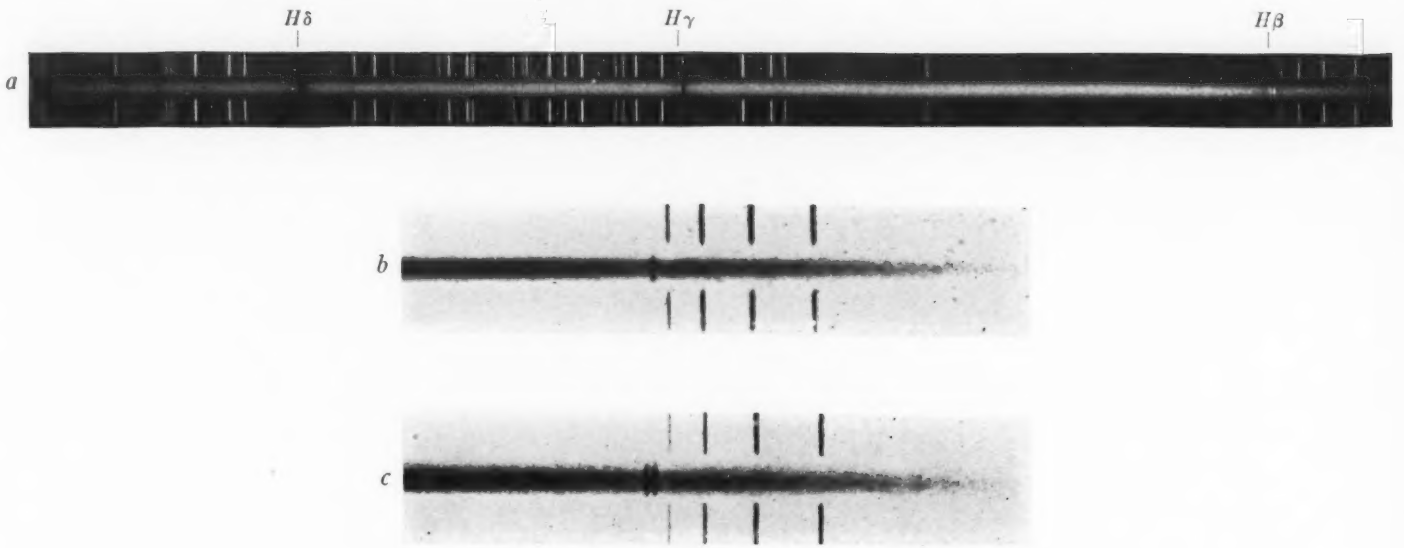
The chief lines in the blue-violet region are those of hydrogen, helium, magnesium, and iron. $H\beta$ consists of a very broad, weak, dark line, upon which are superposed two bright components about 4.2 A apart. The component of longer wave-length, *Er*, is always conspicuous, its intensity changing little if any. The violet compo-

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 423.

[2] H.D. 50138, B.D. −6°1775; 1900 R.A. $6^h46^m7$, Dec. −6°51′; mag. 6.62; spectrum, Harvard B9, Mt. Wilson B8ev.

[3] *Publications of the Astronomical Society of the Pacific*, **33**, 112, 1921; *Mt. Wilson Contr.*, No. 294; *Astrophysical Journal*, **61**, 389, 1925.

## PLATE III




SPECTROGRAMS OF H.D. 50138

*a*) γ14762, 1926 Dec. 14. Intensity $H\beta$ $Ev=5.0$
*b*) γ12179, 1923 Oct. 3, $H\beta$ line. Intensity $H\beta$ $Ev=0.4$
*c*) γ17161, 1929 Dec. 22, $H\beta$ line. Intensity $H\beta$ $Ev=10.5$

nent, *Ev*, on the other hand, undergoes large changes in intensity: at times it is fully as strong as *Er;* at other times it is so weak as to be scarcely recognizable (see Plate III). $H\gamma$ is a strong, narrow absorption line, with weak bright borders visible on some plates. $H\delta$ is a still more intense absorption line with an occasional trace of a bright border.

The helium, magnesium, and iron lines are wholly dark. The helium lines are weak and ill defined; λ 4471 was the only line regularly measured, and even for this line the measured displacements lack accuracy. The magnesium line, λ 4481, has in general about the same intensity as λ 4471, but its distinctness appears to vary. Several enhanced iron lines are measurable on many plates and may vary in intensity, although they are never strong.

The following description of the visual region is based on two grating spectrograms, G 117 and G 302 (Table I). *Hα* is a very intense bright line with two components separated by a narrow minimum. Helium D3 is a weak, indistinct absorption line. Sodium D1 and D2 are narrow absorption lines of low intensity. Of great interest is a fairly well-marked bright line at λ 6300.0,[1] which probably is the forbidden line of neutral oxygen recently identified by I. S. Bowen[2] and F. Paschen[3] with a weak line in the spectra of gaseous nebulae. The companion line λ 6363 is faintly visible on both plates.

Table I gives the journal of observations: the estimated intensity of the violet emission component of $H\beta$, *Ev*, when that of the red component, *Er*, is assumed to be 10, and the measured displacements of various lines. The C and $\gamma$ plates were taken with one-prism spectrographs attached to the 100-inch and 60-inch telescopes, respectively. The dispersion at $H\gamma$ is about 35 A per millimeter. Seed 30 or Eastman 40 emulsions were used throughout, the spectra being widened to increase the distinctness of the lines. All the plates were measured twice by the writer, except C 3205, on which the comparison spectrum is defective. The G plates, at the end of the table, are of the visual region with a dispersion of 66 A per millimeter. They

[1] Wave-length derived by assuming the same displacement measured for the central minimum of *Hα*.

[2] *Physical Review*, **36**, 600, 1930.

[3] *Naturwissenschaften*, **34**, 753, 1930.

TABLE I

| Plate No. | Date | J.D. | Int. $H\beta$ Ev | Displacements in Km/Sec. | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $H\beta$ Ev | $H\beta$ Er | $H\beta$ Abs | $\mu$* | 4471 He | 4481 Mg | Fe |
| | | 2420000+ | | | | | | | | |
| C 817 | 1920 Dec. 26 | 2685.92 | 4.4 | − 71.8 | +137.8 | +26.2 | +24.2 | +48.4 | + 57.0 | ..... |
| γ 10756 | 1922 Jan. 13 | 3068.85 | 10.0 | 115.6 | 146.8 | +21.0 | +34.3 | 25.0 | 29.6 | +35.5 |
| C 1551 | Feb. 11 | 3097.76 | 4.9 | 123.2 | 161.4 | − 6.9 | +16.8 | ..... | ..... | 37.0 |
| 1560 | Feb. 13 | 3099.71 | 0.9 | 148.8 | 165.8 | + 1.2 | +13.5 | 70.9 | 13.7 | 36.5 |
| 1573 | Feb. 16 | 3102.69 | 5.5 | 151.0 | 150.8 | + 1.8 | +24.6 | 83.4 | 71.0 | 40.7 |
| γ 10831 | Feb. 16 | 3102.72 | 6.0 | 139.3 | 141.4 | + 8.4 | + 8.9 | 78.2 | 35.5 | 23.8 |
| 10840 | Feb. 17 | 3103.76 | 3.8 | 142.3 | 153.2 | − 6.0 | +13.9 | 65.0 | 41.6 | 16.7 |
| C 1588 | Feb. 18 | 3104.71 | 3.0 | 97.4 | 156.6 | + 3.0 | +14.0 | ..... | 38.9 | 1.2 |
| γ 10886 | Mar. 9 | 3123.72 | 1.6 | 129.5 | 132.8 | −10.8 | + 5.4 | ..... | 43.6 | ..... |
| 10909 | Mar. 13 | 3127.63 | 6.6 | 113.6 | 128.2 | + 2.6 | +14.9 | ..... | ..... | ..... |
| C 1614 | Mar. 17 | 3131.68 | 3.2 | 132.8 | 161.5 | + 3.9 | +28.1 | 26.6 | 35.8 | 50.4 |
| 1619 | Mar. 18 | 3132.74 | 2.4 | 115.9 | 159.0 | + 8.8 | +20.6 | ..... | 47.1 | ..... |
| γ 10941 | Mar. 20 | 3134.64 | 0.9 | 164.6 | 129.0 | −18.7 | −11.0 | ..... | ..... | ..... |
| C 1661 | Apr. 13 | 3158.64 | 8.3 | 95.7 | 155.4 | +25.8 | +31.3 | ..... | 87.4 | ..... |
| 1671 | Apr. 15 | 3160.64 | 4.7 | 96.5 | 141.6 | +24.1 | +22.2 | 88.8 | ..... | ..... |
| 1672 | Apr. 16 | 3161.65 | 7.5 | 128.0 | 150.0 | +16.4 | +17.1 | 32.9 | 49.5 | 55.3 |
| 1674 | Apr. 17 | 3162.66 | 5.6 | 117.7 | 155.0 | +23.0 | +16.8 | ..... | ..... | 29.5 |
| 1868 | Sept. 5 | 3304.02 | 9.7 | 57.6 | 148.0 | +50.6 | +36.3 | 29.0 | 68.1 | 50.6 |
| 1881 | Sept. 9 | 3308.02 | 9.2 | 81.5 | 142.2 | +29.6 | +37.0 | 72.4 | 53.9 | 57.4 |
| 1915 | Oct. 1 | 3330.03 | 6.7 | 73.2 | 157.8 | +14.1 | +19.7 | 90.4 | 70.5 | ..... |
| γ 11362 | Oct. 5 | 3334.03 | 0.3 | 87.6 | 145.6 | −11.1 | +14.2 | ..... | ..... | 8.5 |
| 11375 | Oct. 7 | 3336.02 | 2.1 | 100.6 | 149.3 | +18.5 | +13.9 | 34.5 | ..... | ..... |
| 11393 | Oct. 10 | 3339.04 | 1.3 | 118.0 | 120.4 | −11.2 | +16.8 | 39.2 | 65.2 | ..... |
| 11398 | Oct. 11 | 3340.03 | 2.5 | 143.0 | 137.4 | −17.2 | +10.2 | 50.2 | 67.9 | ..... |
| 11506 | 1923 Jan. 4 | 3424.88 | 1.2 | 181.8 | 140.6 | −23.8 | −17.0 | 55.0 | 15.4 | ..... |
| 11511 | Jan. 5 | 3425.88 | 0.7 | 179.9 | 130.2 | −28.0 | −20.9 | 54.4 | 46.3 | ..... |
| C 2061 | Jan. 6 | 3426.84 | 1.8 | 179.4 | 139.0 | −30.1 | −10.0 | 46.1 | 81.6 | ..... |
| γ 11541 | Jan. 8 | 3428.79 | 2.4 | 146.6 | 143.4 | −22.4 | − 6.1 | 35.2 | 69.9 | ..... |
| 11601 | Feb. 5 | 3456.82 | 5.1 | 100.4 | 139.8 | + 6.9 | +13.5 | 64.7 | 25.0 | 38.2 |
| 12166 | Oct. 1 | 3695.00 | 0.5 | 111.6 | 121.2 | −14.4 | + 6.5 | 90.1 | 35.3 | ..... |
| 12179 | Oct. 3 | 3697.02 | 0.4 | 119.8 | 118.2 | −16.4 | − 7.1 | 17.2 | 41.7 | ..... |
| 12234 | Oct. 25 | 3718.95 | 7.2 | 129.6 | 130.8 | +10.4 | + 7.2 | 32.6 | 43.8 | ..... |
| C 2521 | Oct. 28 | 3722.05 | 1.2 | 95.4 | 131.6 | + 8.2 | +16.6 | 72.6 | 53.0 | ..... |
| 12266 | Nov. 1 | 3725.95 | 1.6 | 125.9 | 155.8 | −10.6 | +15.0 | 35.1 | 51.0 | 32.2 |
| 12316 | Nov. 28 | 3752.87 | 0.8 | 148.2 | 146.2 | −31.6 | + 4.2 | 64.9 | 61.0 | 23.0 |
| 12335 | Dec. 16 | 3770.92 | 3.1 | 108.2 | 133.5 | + 1.8 | +15.2 | 50.0 | 34.7 | 17.8 |
| 2593 | Dec. 24 | 3778.91 | 0.8 | 123.2 | 144.4 | −19.4 | +11.6 | 67.6 | 37.5 | ..... |
| 2705 | 1924 Feb. 22 | 3838.76 | 2.7 | 144.0 | 157.6 | −10.4 | − 0.8 | 42.8 | 39.2 | 26.2 |
| γ 12515 | Feb. 24 | 3840.72 | 1.8 | 152.0 | 137.2 | −18.4 | − 9.5 | 84.4 | 28.2 | ..... |
| 12518 | Feb. 25 | 3841.67 | 0.5 | 157.4 | 129.2 | −44.2 | − 9.5 | 33.0 | 46.1 | 18.0 |
| 13266 | 1925 Mar. 1 | 4211.67 | 5.9 | 97.5 | 138.8 | +13.4 | +17.6 | 78.6 | 69.6 | 31.4 |
| 13271 | Mar. 2 | 4212.66 | 8.1 | 99.6 | 130.0 | − 0.5 | +12.2 | 35.8 | 36.4 | 39.7 |
| C 3189 | Mar. 4 | 4214.63 | 10.7 | 103.3 | 142.9 | +27.8 | +21.1 | 23.6 | 70.2 | 29.7 |
| 3199 | Mar. 11 | 4221.70 | 9.4 | 82.4 | 166.8 | +28.9 | +28.2 | 47.8 | 39.4 | 17.8 |
| 3205 | Mar. 13 | 4223.64 | 10.4 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 3221 | Mar. 16 | 4226.63 | 5.4 | 101.9 | 148.0 | + 0.2 | + 3.5 | 79.7 | 21.8 | 33.4 |
| γ 13352 | Apr. 7 | 4248.64 | 1.9 | 94.4 | 148.2 | +20.9 | +25.6 | 59.3 | 30.9 | ..... |
| 13357 | Apr. 8 | 4249.65 | 0.6 | 57.1 | 154.1 | +16.9 | +23.8 | ..... | 51.0 | 39.9 |
| C 3245 | Apr. 12 | 4253.64 | 2.9 | 95.5 | 147.6 | +25.6 | +23.2 | 50.0 | 58.2 | 34.4 |
| γ 13994 | 1926 Jan. 25 | 4541.81 | 2.0 | 115.8 | 143.3 | +11.3 | +10.5 | 32.1 | 70.7 | ..... |
| 14012 | Jan. 27 | 4543.80 | 3.2 | 108.2 | 141.1 | + 7.2 | +24.0 | 12.9 | 14.1 | ..... |
| 14018 | Jan. 28 | 4544.71 | 2.5 | 99.7 | 140.3 | − 2.2 | +14.6 | 33.5 | 50.7 | ..... |
| 14021 | Feb. 3 | 4550.78 | 1.3 | 87.5 | 170.3 | +16.1 | +27.5 | 69.1 | 61.5 | ..... |
| 14023 | Feb. 18 | 4565.63 | 0.9 | 134.4 | 114.8 | −20.3 | −22.6 | 31.3 | 33.8 | ..... |
| 14027 | Feb. 20 | 4567.69 | 4.4 | 130.3 | 116.5 | − 6.3 | + 4.3 | (59.9) | (103.2) | ..... |
| C 3702 | Feb. 22 | 4569.74 | 1.6 | 76.8 | 152.7 | + 0.9 | + 5.8 | (69.9) | 72.3 | ..... |
| γ 14050 | Feb. 24 | 4571.68 | 2.9 | 116.8 | 125.1 | −21.7 | + 7.0 | 10.5 | 44.4 | ..... |
| C 3714 | Feb. 26 | 4573.76 | 2.9 | 121.1 | 142.9 | − 0.3 | +14.6 | 70.7 | 45.7 | (34.3) |
| γ 14072 | Feb. 28 | 4575.63 | 2.9 | 119.0 | 134.0 | −12.2 | +15.9 | 43.7 | 29.4 | ..... |
| 14762 | Dec. 14 | 4864.81 | 5.0 | 116.5 | 145.2 | + 0.2 | + 4.7 | 42.4 | 70.3 | 53.3 |
| C 4190 | 1927 Feb. 18 | 4930.64 | 0.7 | 117.1 | 147.0 | +19.3 | +17.3 | 19.2 | 47.9 | 31.2 |
| 4539 | Nov. 10 | 5195.96 | 2.3 | 82.4 | 138.4 | +18.1 | +14.1 | ..... | (38.7) | ..... |
| 4624 | 1928 Jan. 7 | 5253.79 | 2.0 | 98.9 | 162.7 | − 0.8 | +18.4 | 75.8 | 24.8 | 33.4 |
| 5355 | 1929 Nov. 20 | 5937.02 | 10.6 | 98.0 | 129.1 | + 8.8 | +17.8 | (30.1) | (53.5) | ..... |
| 5371 | Dec. 13 | 5959.77 | 8.6 | 92.6 | 155.4 | +28.9 | +31.2 | 34.7 | 50.7 | 43.5 |
| 5372 | Dec. 13 | 5959.82 | 8.7 | −107.5 | +146.1 | +31.3 | +32.2 | +46.7 | + 23.8 | +34.0 |

* The mean displacement of the absorption lines $H\gamma$ and $H\delta$.

TABLE I—*Continued*

| Plate No. | Date | J.D. | Int. $H\beta$ Ev | Displacements in Km/Sec. | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $H\beta$ Ev | $H\beta$ Er | $H\beta$ Abs | $\mu$* | 4471 *He* | 4481 *Mg* | *Fe* |
| C 5375 | 1929 Dec. 13 | 5960.01 | 9.5 | −109.2 | +156.7 | +31.4 | +34.8 | +60.3 | +(62.8) | +33.8 |
| 5379 | Dec. 14 | 5960.91 | 8.0 | 121.8 | 144.1 | +25.1 | +26.5 | 42.0 | 92.7 | 46.0 |
| γ 17140 | Dec. 15 | 5961.91 | 9.1 | 110.5 | 138.2 | +15.4 | +20.4 | ..... | 22.7 | (12.6) |
| 17143 | Dec. 16 | 5962.85 | 10.2 | 94.1 | 163.8 | +20.7 | +10.5 | ..... | ..... | ..... |
| 17145 | Dec. 18 | 5964.80 | 10.0 | 98.5 | 148.9 | +20.0 | +39.5 | ..... | ..... | 41.6 |
| 17161 | Dec. 22 | 5968.88 | 10.5 | 85.2 | 165.9 | +46.9 | +43.6 | ..... | ..... | 53.8 |
| 17168 | Dec. 23 | 5969.80 | 10.7 | − 96.0 | +141.6 | +24.3 | +32.9 | (+3.3) | + 26.7 | +50.8 |
| G 117 | 1926 Jan. 27 | 4543.78 | | | | | | | | |
| 302 | 1930 Feb. 15 | 6023.76 | | | | | | | | |

were taken with a plane-grating spectrograph attached to the 100-inch telescope.

## DISPLACEMENTS OF THE LINES

In a spectrum of this kind it is not safe to assume that all lines have the same displacement. We must therefore examine the measurements in detail to determine which lines may properly be grouped together.

Since the appearance of $H\delta$ resembles that of $H\gamma$, we expect these lines to yield the same displacement within the errors of measurement. The mean difference from 44 plates is $H\delta - H\gamma = +1.07$ km/sec. Rejection of 10 plates showing large differences would reduce the mean to $-0.55$ km/sec. The average difference regardless of sign is 5.8 km (44 plates). The agreement of the two lines, as well as the presence of a displacement common to both, is shown by the correlation plot in Figure 1. Normal places from four groups formed by drawing lines at right angles to the 45° correlation line are given in Table II, and are represented by crosses in Figure 1.

The displacements of the chief absorption components of $H\gamma$ and $H\delta$ are therefore practically the same, and mean values may properly be used. For these means we adopt the symbol $\mu$.

The central absorption line of $H\beta$ consists of a well-defined minimum between the bright components and can be measured with fair accuracy (see Fig. 5). The systematic difference $\mu - H\beta$, from 72 plates, is +9.8 km/sec. The average difference regardless of sign is 11.6 km/sec. The correlation diagram, Figure 2, shows that when $\mu$ is small, $H\beta$ gives decidedly smaller displacements, but that when

$\mu$ is large, $H\beta$ gives nearly the same values. All six normal places (Table III) fall below the 45° line but approach it for high values.

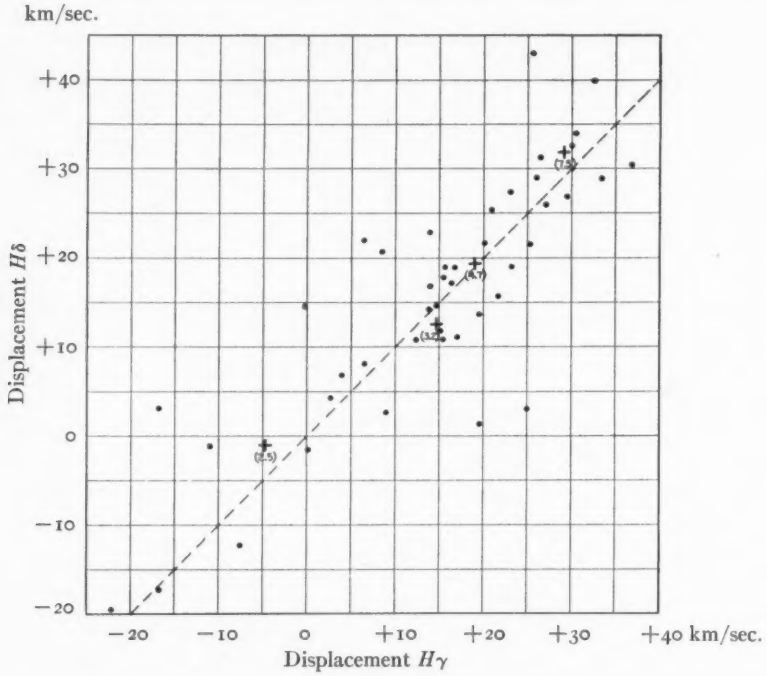



FIG. 1.—Correlation diagram of the displacements of $H\gamma$ and $H\delta$. Crosses represent normal places; the figures near them are mean values of the intensity of $H\beta$ *Ev*.

TABLE II

NORMAL PLACES IN THE DISPLACEMENTS OF $H\gamma$ AND $H\delta$

| No. Plates | $H\gamma$ | $H\delta$ | Int. $H\beta$ *Ev* |
|---|---|---|---|
| | km/sec. | km/sec. | |
| 11 | − 4.8 | − 1.1 | 2.5 |
| 11 | +14.7 | +12.5 | 3.2 |
| 11 | +19.0 | +19.3 | 4.7 |
| 11 | +31.8 | +29.2 | 7.5 |

The displacements of $H\beta$, therefore, should not be combined with those of the other hydrogen lines.

The displacements of the helium line λ 4471 have, curiously, little in common with those of hydrogen. The mean displacement from

57 plates is +49.9 km/sec., while the mean value of $\mu$ from the same plates is only +13.7 km/sec. Individual plates give very scattering

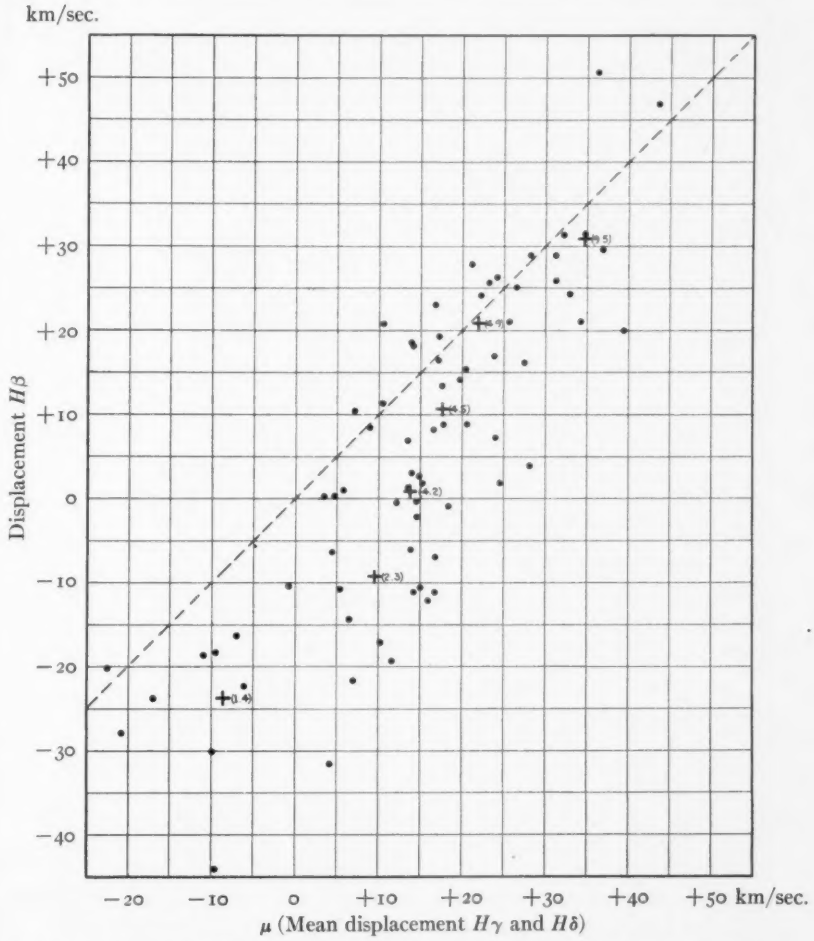



FIG. 2.—Correlation diagram of $\mu$ (mean displacement of $H\gamma$ and $H\delta$) and displacement of $H\beta$. Crosses represent normal places; the figures near them are mean values of the intensity $H\beta$ *Ev*.

results (Table I) which show no definite correlation with $\mu$. Five normal places formed according to increasing values of $\mu$ (Table IV) exhibit no progression with $\mu$ and each is nearly the mean value.

The magnesium line λ 4481 behaves much like λ 4471. The mean

displacement from 62 plates is +48.4 km/sec., while the mean value of $\mu$ from the same plates is only +14.1 km/sec. Results from individual plates are as scattering as those from λ 4471. The third of five normal places formed according to increasing values of $\mu$ (Table IV) has a surprisingly low value, but the results as a whole show no definite progression with $\mu$.

TABLE III

NORMAL PLACES IN $\mu$ AND $H\beta$ ABSORPTION

| No. Plates | $\mu$* | $H\beta$ | Int. $H\beta$ *Ev* |
|---|---|---|---|
| | km/sec. | km/sec. | |
| 12 | − 8.6 | −23.8 | 1.4 |
| 12 | + 9.5 | − 9.3 | 2.3 |
| 12 | +13.7 | + 0.9 | 4.2 |
| 12 | +17.6 | +10.6 | 4.5 |
| 13 | +22.0 | +20.8 | 4.9 |
| 11 | +34.7 | +30.8 | 9.5 |

* $\mu$ represents the average displacement from $H\gamma$ and $H\delta$.

TABLE IV

NORMAL PLACES IN THE DISPLACEMENT OF *He* 4471 AND *Mg* 4481

| No. Plates | $\mu$ | λ 4471 | No. Plates | $\mu$ | λ 4481 |
|---|---|---|---|---|---|
| | km/sec. | km/sec. | | km/sec. | km/sec. |
| 9 | −11.5 | +44.4 | 9 | −11.5 | +44.7 |
| 11 | + 6.6 | 55.5 | 12 | + 6.5 | 55.8 |
| 11 | +14.0 | 52.0 | 12 | +14.0 | 36.9 |
| 13 | +19.7 | 51.0 | 15 | +19.9 | 50.3 |
| 13 | +30.8 | +46.1 | 14 | +30.8 | +52.4 |
| 57 | +13.7 | +49.9 | 62 | +14.1 | +48.4 |

The correlation diagram of λ 4471 and λ 4481 is a scattered array of points with regression lines nearly at right angles. There may be a weak correlation of high values of λ 4471 with low values of λ 4481.

The enhanced iron lines are of low intensity and have been measured on only 38 plates out of 72. While the individual measurements are not of high accuracy, results of interest may nevertheless be drawn from them. The various lines, in the mean, yield accordant displacements (Table V), although on certain individual plates they

agree poorly. The mean displacement from the iron lines on 38 plates[1] is 14.0 km/sec. higher than the value of $\mu$ from the same plates. A decided progression with $\mu$ is shown by the correlation plot (Fig. 3) and by the normal places in Table VI. A comparison with

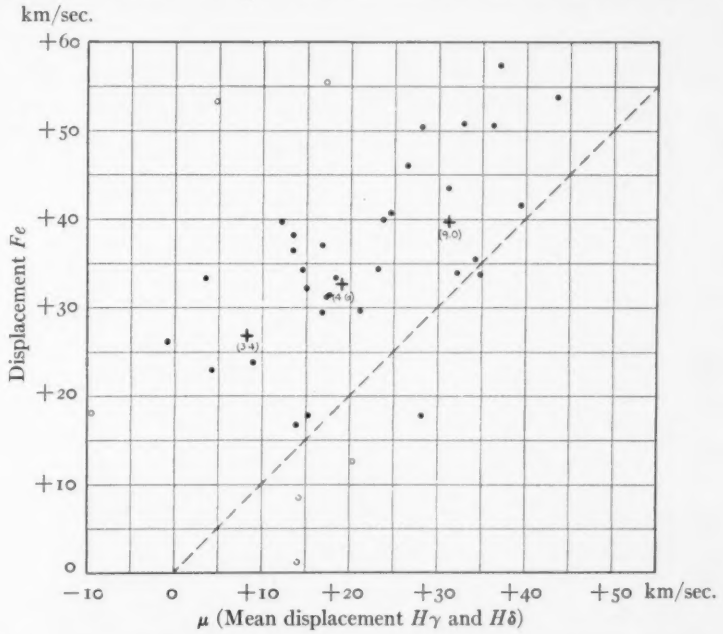



FIG. 3.—Correlation diagram of $\mu$ (mean displacement of $H\gamma$ and $H\delta$) and displacement of iron lines. Crosses represent normal places; the figures near them are mean values of the intensity $H\beta$ *Ev.*

the other data shows that the behavior of iron lines is intermediate between that of hydrogen lines and of λ 4471 *He* and λ 4481 *Mg.*

H and K of calcium are strong, well-defined lines, but were measured on only a few plates as the exposures were timed for $H\beta$ and the region below λ 4000 is usually underexposed. The mean displacement of K on 8 plates is +19.5 km/sec.; the value of $\mu$ from the same plates is +16.7 km/sec. H, measured on 3 plates, gives +17.3 km/sec. The sodium lines, D1 and D2, are of low intensity and

[1] The mean value, +34.0 km/sec., in Table V is the mean of the adopted iron displacements for 38 plates; the mean of all individual line values is +34.9 km/sec. This slight difference arises from the fact that individual values have different effective weights in the two means.

their mean displacement measured on the 2 grating plates, +41 km/sec., is not reliable. H and K, as well as D1 and D2, are probably of stellar origin and are not detached lines.

We now inquire whether the variations in the displacements of the hydrogen lines correspond to orbital motion. Figure 4 shows the individual values of $\mu$ plotted against a condensed time scale. Normal places, represented by crosses, show considerable differences

TABLE V

MEAN DISPLACEMENTS OF IRON LINES

| λ | Mean Vel. | No. Plates |
|---|---|---|
| | km/sec. | |
| 4233.16 | +35.5 | 30 |
| 4549.47 | 33.4 | 20 |
| 4583.84 | 34.5 | 17 |
| 4923.92 | +39.5 | 5 |
| All *Fe* II | +34.0 | 38 |
| $\mu$ | +20.0 | 38 |

TABLE VI

NORMAL PLACES IN THE DISPLACEMENTS OF IRON LINES

| No. Plates | $\mu$ | *Fe* II |
|---|---|---|
| | km/sec. | km/sec. |
| 13 | + 8.2 | +26.8 |
| 13 | 19.0 | 32.7 |
| 12 | +31.1 | +39.6 |

from group to group. Mean values of the displacements of $H\beta$ absorption, plotted as triangles, follow a similar course, suggesting, rather uncertainly, a period of about five years. The groups of plates with their limits in Julian days are given in Table VII.

The range within certain groups, particularly Nos. 1, 2, and 5, however, is a large fraction of the total range and seems clearly to indicate changes measured by days or weeks. In group 1, for example, a sharp maximum is included between J.D. 2423123 and 2423134; and in group 4 there is a maximum near J.D. 2424220. Several configurations suggest a period of about thirty days, but if

this period is persistent, then other features of the curve are apparently variable. An attempt to represent the observations by a combination of two or more periods or by an orbit with changing ele-

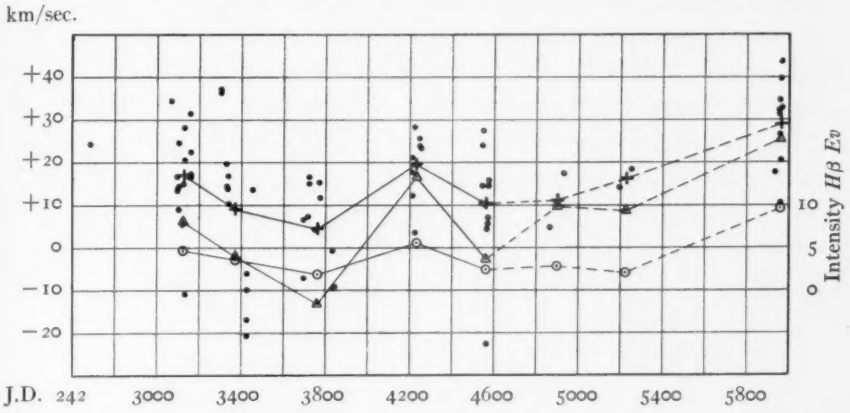



FIG. 4.—Several quantities plotted against the time: dots, individual values of $\mu$ (mean displacement of $H\gamma$ and $H\delta$); crosses, normal places for $\mu$; triangles, normal places for displacements of $H\beta$; circles, normal places for intensity $H\beta$ *Ev*.

TABLE VII

SPECTROGRAMS GROUPED ACCORDING TO TIME

| GROUP | PLATE NOS. | JULIAN DAY | | NO. PLATES | $\mu$ | DISPL. $H\beta$ ABS. | INT. $H\beta$ *Ev* |
|---|---|---|---|---|---|---|---|
| | | Limits | Mean | | | | |
| | | 2420000+ | | | km/sec. | km/sec. | |
| 1..... | γ 10756–C 1674 | 3068–3162 | 3123 | 16 | +17.0 | + 6.1 | 4.7 |
| 2..... | C 1868–γ 11601 | 3304–3456 | 3371 | 12 | 9.0 | − 2.0 | 3.6 |
| 3..... | γ 12166– 12518 | 3695–3841 | 3762 | 11 | 4.5 | −13.2 | 1.9 |
| 4..... | 13266–C 3245 | 4211–4253 | 4230 | 8 | 19.4 | +16.6 | 5.6 |
| 5..... | 13944–γ 14072 | 4541–4575 | 4561 | 10 | 10.2 | − 2.8 | 2.5 |
| 6..... | 14762–C 4190 | 4864–4930 | 4898 | 2 | 11.0 | + 9.8 | 2.8 |
| 7..... | C 4539– 4624 | 5195–5253 | 5225 | 2 | 16.2 | + 8.6 | 2.2 |
| 8..... | 5355–γ 17168 | 5937–5969 | 5961 | 10 | +28.9 | +25.3 | 9.6 |

ments is of doubtful value, however, because the spectrograms now available do not permit a detailed investigation of this kind. Additional spectrograms taken every other night for two or three months would shed considerable light on the problem.

## STRUCTURE OF THE HYDROGEN LINES

$H\beta$ consists chiefly of two well-separated emission lines, *Ev* and *Er*. On many plates these components appear superposed on a very

broad weak absorption line with ill-defined outer limits. At times they are of equal intensity, but at other times *Ev* nearly disappears while *Er* remains approximately constant. The intensities of *Ev* (*Er* = 10) given in Table I are the means of five visual estimates, two by Miss Burwell and three by the writer.

The mean values for the groups of plates listed in Table VII exhibit essentially the same behavior as the displacements (Fig. 4). This is also true in detail for groups 1, 2, and 4; in the other groups the relationship is not clearly brought out. In the last group the values are all high. The law governing the striking changes in *Ev* is not obvious and apparently is not a simple one. The remarks in a previous paragraph concerning the mathematical representation of the wave-length displacements $\mu$ apply largely also to the variations in the intensity of $H\beta$ *Ev*.

The bright portions of $H\gamma$ are much less intense than those of $H\beta$, being, in fact, scarcely recognizable on certain plates. The absorption line, on the other hand, is much stronger than at $H\beta$, and its edges are sharp. The central absorption at $H\beta$ might be considered merely as a minimum between the emission lines, for it does not drop below the level of the spectrum just outside the emission, but at $H\gamma$ the bottom of the absorption line is far below the level of the neighboring spectrum and its position is not controlled by the weak emission edges.

We should expect the weak emission edges of $H\gamma$ to behave much like the emission components of $H\beta$, and to a certain extent this is true, but the generally greater relative strength of the violet edge of $H\gamma$ constitutes a curious anomaly. To display this numerically, estimates of the intensities at $H\gamma$ were made in the same manner as for $H\beta$. Individual estimates have little accuracy, but combined into six groups according to the intensity of $H\beta$ *Ev* they show the behavior quite well (Table VIII). When the components of $H\beta$ are equal, $H\gamma$ *Ev* is stronger than *Er;* when $H\beta$ *Ev* = 5 (half as strong as *Er*), the bright edges of $H\gamma$ are of equal intensity; and when $H\beta$ *Ev* is only 0.7, $H\gamma$ *Ev* is 5. The emission edges at $H\delta$ are very weak, but as far as may be judged they behave like those at $H\gamma$.

The mean separation of the bright portions of $H\gamma$, measured on 21 plates, is 3.60 A. At $H\beta$ the separation varies with the intensity

of *Ev* from 4.32 A to 3.95 (Table VIII). The separation of the intense bright components of *Hα* measured on the two grating plates is 4.24 A.

The position of *Hβ Er* shows little dependence on the intensity of *Ev*. The values of the apparent velocity of *Er* in Table VIII agree

TABLE VIII

COMPARISON OF INTENSITY *Hβ Ev* WITH OTHER DATA

| No. Plates | Intensity *Ev* | | Sep. *Hβ* | Apparent Velocity in Km/Sec. | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | μ | *Hβ* | | | |
| | *Hβ* | *Hγ* | | | Abs. | Mean *Ev, Er* | *Ev* | *Er* |
| | | | A | | | | | |
| 12..... | 0.7 | 5 | 4.32 | + 1.7 | −13.9 | + 4.0 | −129.1 | +137.1 |
| 13..... | 1.6 | 7 | 4.29 | 9.2 | − 2.3 | 12.6 | 119.7 | 144.9 |
| 14..... | 2.8 | 9 | 4.22 | 13.9 | − 1.3 | 13.8 | 116.5 | 144.2 |
| 12..... | 5.1 | 10 | 4.21 | 14.2 | + 7.1 | 14.2 | 115.7 | 144.1 |
| 9..... | 7.7 | 10 | 4.07 | 21.4 | +17.1 | 18.7 | 106.8 | 144.2 |
| 12..... | 10.0 | 12 | 3.95 | +29.7 | +27.1 | +27.4 | − 94.3 | +149.2 |

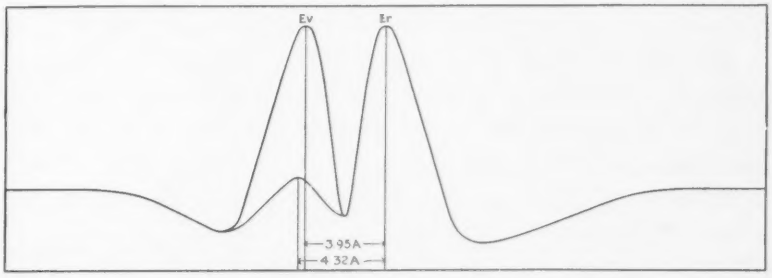



FIG. 5.—Intensity-curve of *Hβ*. The position and intensity of the red emission component *Er* remain practically unaltered, but the violet component *Ev* undergoes great variation in intensity and a slight variation in position as indicated.

closely, except that the first is 7 km/sec. low, and the last 5 km/sec. high. The displacement of *Ev*, on the other hand, shows a decided progression through 35 km/sec. from (algebraically) low to high values. This is reflected in the mean separations of the bright components (fourth column), which show that as *Ev* increases in strength it approaches *Er*. The changes in *Hβ* are illustrated by the sketched intensity-curve in Figure 5, which shows the extremes of intensity for *Ev*. When the intensity is low, the maximum (or effective center)

of *Ev* is displaced toward shorter wave-lengths. The central absorption lines of $H\beta$, $H\gamma$, and $H\delta$ are then also displaced in the same direction (see Tables II, III, and VIII; also Figs. 2, 3, and 4). The displacements of the point halfway between the effective centers of $H\beta$ *Ev* and *Er* (denoted "Mean *Ev*, *Er*" in Table VIII) are similar to the values of $\mu$ and are in general algebraically larger than the displacements of the central absorption at $H\beta$. The means of all plates are: $\mu+14.6$ km/sec.; $H\beta$ Mean *Ev*, *Er*$+15.0$; $H\beta$ Abs. $+4.9$.

## DISCUSSION

The outstanding problem in this spectrum lies in the great changes in the intensity of the violet emission component of $H\beta$. Its solution would probably shed considerable light on the general problems of Be and other early-type stars, and perhaps on those of novae. When the violet component is weak, the asymmetry of the line recalls that occurring in the spectra of novae, although in H.D. 50138 the strong bright component *Er* is not near the normal position of the line as in novae, but lies about 2 A toward the red. The hydrogen lines in the companion to *o* Ceti behave similarly,[1] but certain other Be stars, e.g., P Cygni[2] and D.M. $-27°11944$,[3] more closely resemble novae in this respect. In typical Be stars the emission at the Balmer lines is regularly double, and numerous instances of variation in the intensities of the components have been recorded; but the $H\beta$ line[4] in the spectrum of H.D. 50138 presents one of the most striking examples known to the writer.

Are the changes intrinsic or are they caused by variable absorption? It seems natural to assume that the duplicity of the bright lines in this and other Be spectra is a result of a "self-reversal" analogous to that in the electric arc, the bright components thus being not two independent lines but the portions of an underlying broad bright line left on either side of the narrow region of absorp-

[1] See p. 362.

[2] *Lick Observatory Bulletins*, **8**, 24, 1913.

[3] *Mt. Wilson Contr.*, No. 295; *Astrophysical Journal*, **61**, 418, 1925.

[4] The rapid decrease in the intensity of the emission in passing to the more refrangible members of the Balmer series, as well as the increase in the absorption, is associated with the later subdivisions of class B. In class Bo, for example, it is usually more gradual.

tion. If the bright line is broadened by the close approach of electrons and positive ions to the emitting atom (Stark effect), the narrower central absorption doubtless arises in a higher, more tenuous stratum where such approaches are less frequent. Under such circumstances, however, it is difficult to imagine an occurrence that would reduce the intensity of *Ev* to one-tenth of its normal value without affecting *Er*. If, to take another hypothesis, the bright line is broadened by rotation, we must suppose the central absorption to occur in a layer which, if it takes part in the rotation, is so far above the level of emission as to have but a relatively small component of motion in the line of sight. Whether it is physically possible for the chromosphere of a Be star to have such a structure as this suggestion demands is certainly open to question; but if we admit it for the sake of argument, we may suppose *Ev* to be weakened by the partial occultation, by another body, of emitting gases above the approaching limb. This hypothesis seems too artificial to deserve extended discussion unless later it finds support in a plausible interpretation of the measured wave-length displacements of various lines. One further remark may be made in partial answer to the question at the beginning of this paragraph, namely, that if the absorption of an overlying layer of hydrogen is responsible for the changes in $H\beta$ *Ev*, then this absorption must differ in some manner from that which produces the central dark lines of the Balmer series. This latter type is more intense at $H\gamma$ and $H\delta$ than at $H\beta$, and if called into play to reduce the intensity of $H\beta$ *Ev* by 90 per cent, should at $H\gamma$ and $H\delta$ produce strong absorption nearly 2 A to the violet of the ordinary dark line. This would widen those lines and give them abnormally large negative shifts. Neither of these effects is present to the degree to be expected, but, curiously enough, traces of both may be found. On a few plates on which $H\beta$ *Ev* is weak, the absorption line at $H\gamma$ is unsymmetrical, the violet edge being less sharp than the red; but the effect is slight. The phenomena correspond more nearly to a weakening of the feeble emission on the violet edge of $H\gamma$ proportional to the decrease of intensity of $H\beta$ *Ev* than to the action of atomic absorption on the violet sides of the lines. The mechanical occultation of an emitting hydrogen chromosphere suggested above might account for this phenomenon. As to the nega-

tive shifts, the centers of the dark $H\gamma$ and $H\delta$ lines are indeed displaced toward shorter wave-lengths when $H\beta$ *Ev* is weak; but the displacements are less than the similar shifts of the central absorption at $H\beta$.

Several facts concerning the line displacements are puzzling. The failure of the bright portions of the hydrogen lines to shift with the absorption centers is a feature of primary importance. The same general phenomenon occurs in other Be stars and should be carefully observed wherever possible. No explanation of the extraordinary independence of behavior of λ 4471 and λ 4481 can be hazarded. The displacements of the iron lines show a dependence, though not close, on those of the hydrogen lines. Measurements of a single plate of H.D. 160095[1] showed the displacements of the iron lines to be intermediate between those of hydrogen and the larger ones of λλ 4471, 4481, as in H.D. 50138. These results recall the general fact that in Be stars the lines of ionized iron more often resemble those of hydrogen than do those of helium or magnesium.

It remains to mention a remarkable similarity between the behavior of the hydrogen lines in the spectrum of H.D. 50138 and in that of the companion to *o* Ceti as observed by Joy.[2] The emission components are more intense in the companion than in H.D. 50138, and the general appearance of the lines is not identical, but the changes in structure are surprisingly alike in the two stars. This is brought out by Figure 9 in Joy's paper and by the following quotations and remarks:

1. "The hydrogen lines are made up of three parts: a strong emission component . . . . displaced about 2 A to the red . . . . ; a strong absorption line . . . . ; and *a violet emission component of variable strength* lying 3 A to the violet."

2. "There is no certain indication of variation in the position or intensity of the red emission component."

3. "The violet component is stronger with respect to the red in $H\delta$ than in $H\beta$."

4. "The absorption seems to fall farther to the violet as the violet

[1] *Mt. Wilson Contr.*, No. 409; *Astrophysical Journal*, **72**, 98, 1930.

[2] *Mt. Wilson Contr.*, No. 311; *Astrophysical Journal*, **63**, 335, 1926.

component becomes weaker, but this effect may be apparent rather than real."

5. Unpublished measurements by Mr. Joy which he has kindly brought to my attention show that the violet component of $H\gamma$ moves to the violet as it becomes weaker.

6. A periodicity in the changing intensity of the violet component was not clearly revealed, but a cycle of about five years combined with a shorter one, possibly the period of the variable star, three hundred and thirty days, was suggested.

Lines other than those of hydrogen are not at all similar in the two stars.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
November 1930

# THE SPECTRUM AND RADIAL VELOCITY OF AC HERCULIS[1]

By ROSCOE F. SANFORD

ABSTRACT

*Photometric observations.*—The visual and photographic light-curves of AC Herculis give evidence of light-variation of the RV Tauri class, are consistent with a large change in spectral class between the maxima and primary minimum, and are represented by Waterfield's formula,

$$\text{Light min.} = \text{J.D. } 2414461.1 + 75^d.4 + 6^d.1 \sin (157°.5 + 2°.045\, E) \text{ G.M.T.}$$

*Spectroscopic observations.*—Mount Wilson spectrograms extend from 1924 to 1930. From primary to secondary maximum the enhanced lines dominate the F1-type spectrum. As the star wanes toward minimum the arc lines are very numerous, and finally at and near minimum, when the spectral class most nearly resembles K4, certain very conspicuous low-temperature lines appear. The G band varies consistently with these changes.

The hydrogen lines are always present in absorption, but have emission borders from light-minimum until primary light-maximum is passed, and again faintly at phase 42 days. The red component, which for a brief interval at the beginning is the stronger, dwindles very rapidly and 7 days after light-minimum can no longer be seen. At phase 42 days only the violet component appears.

Mean radial velocity-curves have primary and secondary maxima and minima which follow the minima and maxima of the light-curve with a lag of about 7 days.

Both the velocity of the system and the shape of the velocity-curve appear to vary.

The enhanced lines give a mean velocity of $-25$ and the arc lines $-31.9$ km/sec. The difference is larger than, but has the same sign as, that found for certain other stars.

The differences between the velocities from the absorption lines of hydrogen and from the arc lines follow a curve having two maxima and two minima. The most rapid changes in the curve just precede, and its maxima occur at, the light-maxima. This may be explained by oscillations (synchronous with the light-variation) of the emission borders, which vary in relative intensity.

## PHOTOMETRIC RESULTS

AC Herculis[2] was discovered to be a variable by Miss Dorothy Applegate[3] in 1921. The spectrum then assigned was F8. Subsequently (April, 1922—December, 1923) Leiner[4] made a series of photometric observations by Argelander's method and concluded that it is a variable of the RV Tauri class, and that primary mini-

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 424.

[2] B.D.+21°3459; Berl. B 6501; H.D. 170756; $\alpha$ 18$^h$26$^m$0, $\delta$ +21°48′(1900).

[3] *Harvard Circulars*, No. 225, 1921.

[4] *Astronomische Nachrichten*, **221**, 247, 1923

mum, from which the period is most satisfactorily determined, is represented by the expression

$$\text{J.D. } 2423212.18 \text{ G.M.T.} + 75^{d}.933E .$$

Zacharov[1] obtained observations, also by Argelander's method, from May to December, 1923, thus covering a part of the interval over which Leiner observed. His observations, plotted with a period of 75 days, appear in Figure 1*a*.

Waterfield[2] derived the light-variation from the sky-patrol plates obtained at the Harvard College Observatory in the interval 1898–1926. He concludes from a large number of observed minima and from many more inferred from the run of adjacent observations that the period, although close to 75 days, is not constant, and that the expression

$$\text{Primary min.} = \text{J.D. } 2424461.1 + 75^{d}.4E + 6^{d}.1 \sin (157^{\circ}.5 + 2^{\circ}.045E) \text{ G.M.T.}[3]$$

furnishes the best means of deriving phases for the observations in the interval 1898–1926. His mean light-curve plotted in Figure 1*b* is of course photographic.

All three series of observations agree in showing double maxima and double minima. The minima of Leiner's and Zacharov's measures are satisfactorily represented by Waterfield's formula.

The first two lines of Table I compare the maxima, $M1$ and $M2$, and minima, $m1$ and $m2$, of Leiner's and Zacharov's curves; the third line is the mean of the first two, while the fourth gives the values for Waterfield's photographic curve.

The first two curves agree well except for secondary minimum. For this the difference may be only accidental, although if AC Herculis is a variable of the RV Tauri class, secondary minimum may vary in depth. During the longer interval covered by Leiner's observations this might produce in his curve a shallower mean secondary minimum. Indeed, the plot of Leiner's observations

[1] *Ibid.*, p. 136, 1923; **222**, 295, 1924.

[2] *Harvard College Observatory Bulletins*, No. 845, 1927.

[3] In Waterfield's paper $-6^{d}.1$ is given erroneously for $+6^{d}.1$.

shows that in 1922 his secondary minima are a little brighter than in 1923, when they agree fairly well with Zacharov's.

The difference Pg−Vis for $M1$ from the third and fourth lines of Table I is −0.48 mag. This difference may be affected by variability in the maximum light, but even so there is probably a large

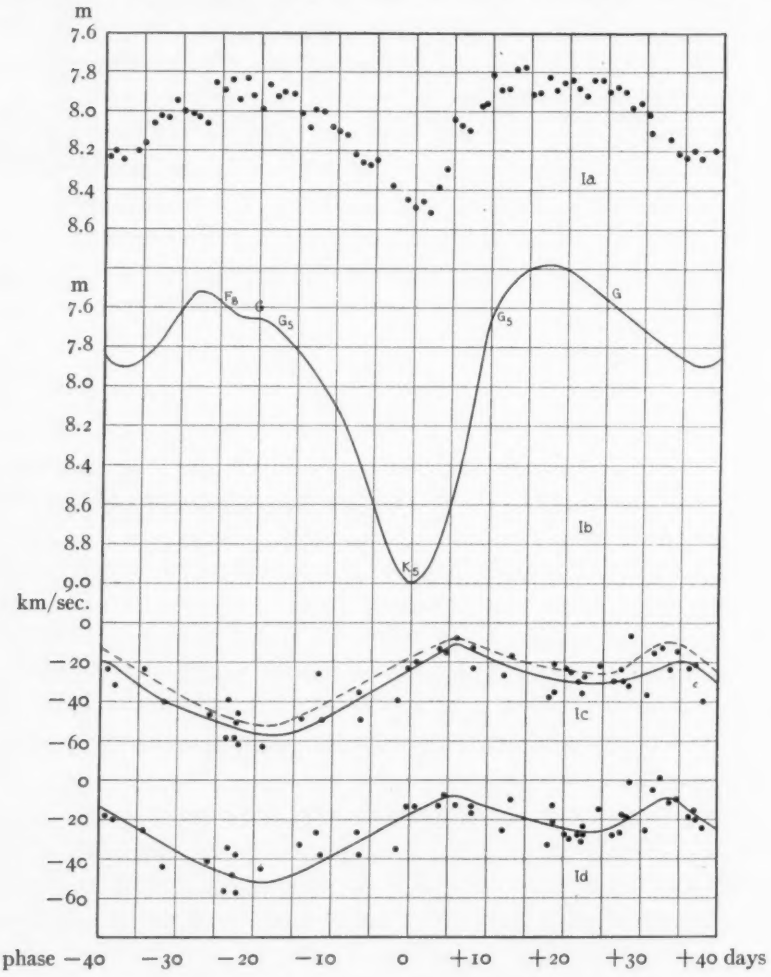



FIG. 1.—*a*, Leiner's visual light-curve; *b*, Waterfield's photographic light-curve and estimated spectral types; *c*, individual velocities from the arc lines; *d*, individual velocities from the enhanced lines. Solid lines in *c* and *d* are the mean curves for their respective velocities. That of *d* is repeated with the broken line in *c*.

relative error in the zero points of the magnitude scales. An arbitrary correction of −0.84 mag. applied to the visual magnitudes gives at the time of $M1$ a color-index agreeing with the observed spectral type F1. The resulting color-indices and their corresponding spectral types for other phases are in the last two lines of Table I. The calculated types agree well with the observed values, as will be seen later.

TABLE I

| | $M1$ | $m1$ | $M2$ | $m2$ |
|---|---|---|---|---|
| Leiner | $7^m89$ | $8^m52$ | $7^m95$ | $8^m08$ |
| Zacharov | 7.84 | 8.46 | 7.90 | 8.22 |
| Mean | 7.86 | 8.49 | 7.92 | 8.15 |
| Waterfield | 7.38 | 9.00 | 7.52 | 7.90 |
| Corrected mean Visual magnitude | 7.02 | 7.65 | 7.08 | 7.31 |
| Color-index | 0.36 | 1.35 | 0.44 | 0.59 |
| Spectrum | F1 | K3 | F4 | F8 |

Table II shows the intervals between primary minimum ($m1$) and the other three points, primary maximum, secondary minimum, and secondary maximum. There is general agreement for the three curves, although $M2$ for the photographic curve occurs several days earlier than for the visual curve, and $M1-m1$, which agrees well for Zacharov and Waterfield, is three days larger for Leiner's curve.

TABLE II

| | $M1-m1$ | $m2-m1$ | $M2-m1$ |
|---|---|---|---|
| Leiner | $21^d$ | $38^d$ | $54^d$ |
| Zacharov | 18 | 36 | 52 |
| Waterfield | 18 | 36 | 47 |

These differences are only a part of the evidence that the light-curves vary in shape. Another item, already alluded to, is the difference between Leiner's and Zacharov's curves at the secondary minimum. Furthermore, Waterfield has compared the photographic light-curves based on observations before and after 1915 (his Figs. 4*a* and *b*) and finds that the later differs from the earlier in having a more rounded primary maximum, a sharper secondary minimum,

and a sharper secondary maximum which differs in magnitude from primary maximum less than was the case previous to 1915. Qualitatively these results point to a light-variation of the RV Tauri class.

Spectral types as determined at Harvard are:

| Phase | Spectral Type |
|---|---|
| $0^d$ | K5 |
| 10 | G5 |
| 24 | G |
| 51 | F8 |
| 55 | G |
| 58 | G5 |

The results are also indicated in Figure 1*b*. The photometric observations therefore show that AC Herculis has a period of a little over 75 days, that there are two maxima and two minima, that there is evidence of variability in the shape of the light-curve, and that the ranges in photographic and visual light are consistent with an increase of approximately two spectral divisions in passing from maximum to minimum light. Objective-prism spectra show a change from F8 at maximum to K5 at minimum.

## SPECTROGRAPHIC RESULTS

The first slit spectrogram was obtained at Mount Wilson in 1924. Four were obtained in 1925, thirteen in 1926, eighteen in 1927, sixteen in 1928, seven in 1929, and fourteen in 1930. Table III gives a list of these spectrograms, their Greenwich mean times of observation, their phases (always from minimum) reckoned from Waterfield's formula, etc. C indicates a plate obtained with a one-prism spectrograph at the 100-inch telescope and $\gamma$ one taken with similar equipment at the 60-inch telescope. Except as noted in the remarks, all spectrograms fall within the region $\lambda$3900 to $\lambda$5000 and have a dispersion of approximately 37 A per millimeter at $H\gamma$.

A general description of the marked spectral changes follows. The radial velocities will be considered later.

*Spectral changes.*—The changes in the star's spectrum during each period are striking.

Absorption lines from the ionized atoms of iron, titanium, stron-

TABLE III

RADIAL VELOCITIES OF AC HERCULIS

| PLATE | DATE | G.M.T. | PHASE | VELOCITIES IN KM/SEC. | | | | | REMARKS |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean All | Enh. Lines | Arc Lines | Hydr.–Arc | | |
| | | | | | | | Viol. Em. | Absorp. | |
| C 3030 | 1924 Oct. 7 | $16^h13^m$ | $23^d.826$ | −15.1 | ..... | ..... | ..... | ..... | (1) |
| 3310 | 1925 June 4 | 20 05 | 38.197 | − 9.6 | ..... | ..... | ..... | ..... | (1) (2) |
| γ 13522 | July 6 | 16 40 | 70.054 | −26.7 | ..... | ..... | ..... | + 6 | (3) |
| C 3436 | Aug. 5 | 15 55 | 24.623 | ..... | −14.2 | −21.5 | ..... | +12 | ..... |
| γ 13737 | Sept. 24 | 15 52 | 74.531 | −20.0 | ..... | ..... | ..... | −22 | (4) |
| C 3770 | 1926 Apr. 25 | 21 55 | 61.433 | ..... | −32.1 | −49.1 | ..... | − 5 | ..... |
| γ 14214 | May 25 | 22 55 | 16.005 | −34.8 | ..... | ..... | −43 | +37 | (2) |
| C 3801 | 27 | 23 50 | 18.043 | ..... | −33.1 | −38.1 | −52 | +43 | ..... |
| γ 14255 | June 18 | 21 45 | 39.956 | −45.9 | ..... | ..... | ..... | ..... | (4) |
| C 3840 | 22 | 17 52 | 43.795 | ..... | −44.0 | −40.0 | ..... | +43 | ..... |
| 3872 | July 1 | 18 24 | 52.817 | ..... | −48.5 | −58.5 | ..... | +34 | ..... |
| 3888 | 22 | 16 26 | 73.685 | ..... | −35.4 | −39.2 | ..... | − 9 | ..... |
| γ 14387 | 26 | 18 00 | 2.426 | −37.3 | ..... | ..... | ..... | −33 | (4) |
| 14423 | Aug. 15 | 17 04 | 22.311 | ..... | −30.9 | −36.2 | ..... | ..... | ..... |
| 14432 | 17 | 19 22 | 24.407 | −25.7 | ..... | ..... | ..... | ..... | (3) |
| C 3960 | 19 | 18 33 | 26.373 | ..... | −27.6 | −29.3 | ..... | ..... | ..... |
| 4000 | Sept. 15 | 15 17 | 53.237 | ..... | −57.6 | −62.0 | ..... | ..... | ..... |
| γ 14512 | 18 | 15 45 | 56.256 | ..... | −44.8 | −63.2 | ..... | +19 | ..... |
| γ 14862 | 1927 Mar. 17 | 0 39 | 9.282 | −17.0 | ..... | ..... | −83 | ..... | (2) |
| C 4220 | Apr. 12 | 23 58 | 36.254 | ..... | −18.4 | −23.1 | ..... | − 4 | ..... |
| 4234 | 17 | 21 52 | 41.166 | ..... | −25.3 | −23.3 | ..... | +44 | ..... |
| 4259 | May 11 | 19 50 | 65.071 | −38.4 | ..... | ..... | ..... | ..... | (1) |
| γ 14999 | 21 | 21 07 | 75.125 | ..... | −13.4 | −23.6 | ..... | − 2 | ..... |
| 15003 | 22 | 22 35 | 0.786 | ..... | −13.4 | −20.0 | ..... | ..... | ..... |
| C 4290 | June 9 | 19 37 | 18.662 | ..... | −21.0 | −35.3 | ..... | +20 | ..... |
| γ 15025 | 11 | 23 21 | 20.818 | ..... | −29.6 | −25.2 | ..... | + 4 | ..... |
| 15032 | 12 | 22 19 | 21.775 | ..... | −27.7 | −29.9 | ..... | +31 | ..... |
| 15036 | 13 | 17 48 | 22.587 | ..... | −27.3 | −27.6 | ..... | +18 | ..... |
| 15083 | July 8 | 20 17 | 47.690 | −39.0 | ..... | ..... | ..... | ..... | (5) (2) |
| C 4342 | 10 | 17 57 | 49.593 | ..... | −41.6 | −46.5 | ..... | +36 | ..... |
| γ 15174 | Aug. 11 | 16 17 | 6.099 | ..... | −12.2 | − 7.5 | −68 | +15 | ..... |
| γ 15182 | 13 | 16 4 | 8.090 | ..... | −12.8 | −12.7 | −73 | +10 | ..... |
| C 4425 | Sept. 11 | 15 24 | 37.052 | ..... | −14.8 | −21.5 | ..... | +11 | ..... |
| 4427 | 11 | 18 42 | 37.199 | ..... | −19.9 | −31.5 | ..... | +18 | ..... |
| 4449 | Oct. 8 | 15 12 | 64.073 | ..... | −38.0 | −49.3 | ..... | −11 | ..... |
| γ 15313 | 13 | 16 45 | 69.070 | −25.6 | ..... | ..... | ..... | − 4 | (3) |
| 15615 | 1928 Mar. 7 | 0 25 | 63.617 | ..... | −26.4 | −25.9 | ..... | + 5 | ..... |
| 15894 | June 20 | 21 54 | 18.722 | ..... | −12.2 | −20.9 | ..... | +33 | ..... |
| 15906 | 24 | 20 29 | 22.664 | ..... | −23.6 | −27.1 | ..... | +13 | ..... |
| 15929 | 29 | 20 48 | 27.677 | ..... | −17.1 | −28.8 | ..... | − 5 | ..... |
| 15932 | 30 | 19 45 | 28.633 | ..... | − 0.3 | − 6.1 | ..... | + 8 | ..... |
| 15939 | July 3 | 19 50 | 31.636 | ..... | − 4.8 | −15.7 | ..... | +24 | ..... |
| 15944 | 4 | 21 22 | 32.700 | ..... | + 1.6 | −14.8 | ..... | − 5 | ..... |
| C 4885 | 5 | 21 38 | 33.711 | ..... | −11.3 | −24.0 | ..... | ..... | ..... |
| 4889 | 6 | 20 31 | 34.665 | ..... | − 9.5 | −14.5 | ..... | + 5 | ..... |
| 4893 | 10 | 17 58 | 38.559 | −20.3 | ..... | ..... | ..... | +27 | (5) |
| γ 16021 | 28 | 16 38 | 56.503 | −34.8 | ..... | ..... | ..... | ..... | (3) |
| C 4937 | Aug. 23 | 17 45 | 7.185 | −18.0 | ..... | ..... | −62 | +26 | (5) |

TABLE III—*Continued*

| Plate | Date | G.M.T. | Phase | Velocities in Km/Sec. | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean All | Enh. Lines | Arc Lines | Hydr.−Arc | | |
| | | | | | | | Viol. Em. | Absorp. | |
| γ 16126... | 1928 Aug. 29 | 17h15m | 13d164 | ..... | − 9.5 | −16.6 | −57 | +26 | ..... |
| 16187... | Sept. 27 | 15 15 | 42.080 | −38.3 | ..... | ..... | ..... | +25 | (5) |
| C 5051... | Oct. 24 | 15 55 | 69.103 | ..... | −38.0 | −49.3 | ..... | −15 | ..... |
| γ 16254... | 27 | 15 45 | 72.096 | + 2.2 | ..... | ..... | ..... | ..... | (1) |
| C 5158... | 1929 Mar. 29 | 23 52 | 74.735 | ..... | ..... | ..... | ..... | ..... | (6) |
| γ 16550... | Apr. 26 | 22 46 | 27.289 | ..... | −26.4 | −23.6 | ..... | +10 | ..... |
| 16554... | 27 | 22 39 | 28.284 | ..... | −18.5 | −32.0 | ..... | + 8 | ..... |
| 16598... | May 22 | 21 12 | 53.223 | ..... | −38.0 | −45.6 | ..... | + 7 | ..... |
| 16640... | June 17 | 18 42 | 3.774 | ..... | −12.8 | −13.1 | −82 | − 1 | ..... |
| 16838... | Aug. 21 | 16 31 | 68.683 | ..... | −26.4 | −36.7 | ..... | − 8 | ..... |
| C 5340... | Oct. 19 | 15 30 | 51.606 | ..... | −56.6 | −58.4 | ..... | +18 | ..... |
| γ 17350... | 1930 Mar. 19 | 0 39 | 52.007 | ..... | −34.0 | −39.1 | ..... | −25 | ..... |
| C 5441... | Apr. 15 | 22 59 | 4.618 | ..... | − 7.9 | −15.6 | −73 | + 6 | ..... |
| γ 17405... | 17 | 0 9 | 5.666 | −24.1 | ..... | ..... | ..... | ..... | (1) |
| C 5445... | May 11 | 23 30 | 30.639 | ..... | −25.7 | −36.5 | ..... | +18 | ..... |
| γ 17491... | June 5 | 18 59 | 55.451 | −39.8 | ..... | ..... | ..... | ..... | (4) |
| 17551... | July 3 | 17 30 | 8.079 | ..... | −16.6 | −23.5 | −63 | +13 | ..... |
| 17564... | 7 | 17 38 | 12.085 | ..... | −25.3 | −26.4 | −54 | +25 | ..... |
| C 5502... | 15 | 17 27 | 20.077 | ..... | −27.2 | −23.2 | ..... | +35 | ..... |
| 5503... | 15 | 19 02 | 20.143 | ..... | ..... | ..... | ..... | ..... | (7) |
| 5516... | Aug. 13 | 18 35 | 49.034 | ..... | ..... | ..... | ..... | ..... | (7) |
| γ 17697... | 17 | 16 16 | 53.028 | ..... | −49.8 | −50.7 | ..... | +30 | ..... |
| 17701... | 18 | 16 19 | 54.030 | ..... | ..... | ..... | ..... | ..... | (7) |
| 17752... | Sept. 8 | 17 56 | 75.097 | ..... | −16.7 | ..... | ..... | ..... | (4) |
| 17767... | 11 | 16 57 | 2.656 | ..... | ..... | ..... | ..... | ..... | (7) |

REMARKS

(1) Short camera
(2) Poor focus
(3) Poor quality
(4) Underexposed
(5) Overexposed
(6) No comparison spectrum
(7) Red sensitive plate; D lines to *Hα*

tium, scandium, yttrium, and other elements are prominent features of the spectrum most of the time, but their intensity varies considerably in relation to other lines. Three days after minimum light these enhanced lines are conspicuous in a spectrum which also includes many good metallic lines from neutral atoms of elements such as iron. They continue to strengthen relative to lines from the neutral atoms until phase 20 days, after which some diminution is noticeable, although they remain prominent until phase 50 days. By this time the lines of the neutral atoms have become conspicuous, and from then until phase 63 days the spectrum is more

densely crowded with absorption lines than at any other time. Somewhat before the middle of this last interval, such extreme low-temperature lines as λλ 4376, 4427, 4482, and 4489 of iron become prominent and continue to strengthen until at light-minimum they are dominant features of the spectrum. Three days later the enhanced lines are again the outstanding feature and a new cycle of changes begins. Extraordinary disturbances in the star's atmosphere must occur between light-minimum and phase 3 days, for the spectral variation during this interval is almost the greatest that the star undergoes.

The G band, which is the only one conspicuous within the range of wave-length covered by most of the plates, undergoes as notable a change as the line spectrum itself. It is noteworthy for its absence between phases 5 and 25 days, then shows weakly, increasing gradually until it attains its maximum strength between phase 50 days and light-minimum.

Spectrograms representative of all phases were compared by Mr. Joy and the writer with the previously classified spectra of certain Cepheid variables. Their comparisons are in good agreement and show a variation in spectral type from F1 at the light-maxima to K4 at primary light-minimum, with possibly a slight change toward later types between the two light-maxima or at secondary light-minimum.

The lines $H\delta$, $H\gamma$, and $H\beta$ are at all times present in absorption, but during certain phases associated emission can be seen. Just before light-minimum they appear as typical absorption lines, comparable with the stronger metallic lines. Almost precisely at light-minimum they become narrow, and close examination reveals bordering emission which is stronger than the immediately adjacent continuous spectrum. These borders are rather broad and ill defined, the red being the stronger. By 2.4 days after minimum they are fairly well defined, the red component still remaining the stronger; but the violet component has the ascendancy at phase 3.6 days and probably reaches its maximum strength near phase 8.0, whereas the red component cannot be detected with certainty beyond phase 7.2. The violet component, although its intensity diminishes after phase 8.0, can still be found on spectrograms with phases up to 18 days.

The presence of weak emission lines on the violet side on plates C 4234 and C 3840, phases 41.2 and 43.8 days, respectively, and their absence from spectrogram $\gamma$ 16187 taken at the intermediate phase 42.1 would seem to indicate that during this phase interval such emission may attain sufficient strength to rise above the continuous spectrum.

Although there is no recognizable emission at $H\delta$, $H\gamma$, and $H\beta$ at other phases, it may still be there, too weak to rise appreciably above the continuous spectrum, but manifesting itself by shifting the position of the associated absorption line. This will be discussed later.

It is to be noted that the phases for emission lines of hydrogen are also those for the branches of the light-curve which rise rapidly toward light-maxima. Furthermore, the maximum intensity for the more persistent violet component in each case occurs about midway between light-minimum and the succeeding maximum.

The four spectrograms $\gamma$ 17767, C 5503, C 5516, and $\gamma$ 17701, which cover the yellow-red region of the spectrum and whose phases are 2.6, 20, 49, and 54 days, respectively, all show a bright $H\alpha$ line. The first two are evidence of the presence of this line at the extremes of the phase interval 4–18 days, when the more refrangible lines show emission borders, and the last two of its presence at phases when there is no recognizable emission for them. Our observations, however, are too few to answer the question whether $H\alpha$ always appears as a bright line or, if not, at just what phases it does appear as an emission line.

*The radial velocities.*—The spectrograms have been measured with a Gaertner machine and reduced by means of our general stellar-reduction tables. All wave-lengths are therefore upon this basis. Practically all spectrograms of good quality show enough arc and enhanced lines to furnish a velocity from each class separately. These are given in their respective columns in Table III.

In Figure 1*c* all arc-line velocities have been plotted against their phases as dots and are represented by the lower curve. The same procedure has been followed in Figure 1*d* for the velocities depending upon the enhanced lines. The curve which seems best to fit these velocities is also shown in Figure 1*c* (upper curve).

The scattering of the individual velocities about the mean curves

is larger than would be expected for plates such as those used, unless the velocity-curve is subject to fluctuations from cycle to cycle. In order to test for changes in the curve, the arc-line velocities for each of the years 1926–1930 have been plotted separately in Figures 2*a–e*, together with the mean curve from the arc lines (lower curve, Fig. 1*c*). These plots show that most of the points for 1926 are below the mean curve; that those of 1927 fit the mean curve very well; that the evidence for 1928 is inconclusive for the phase interval −40 to +5 days, while, for the remainder of the cycle, the points are mostly above the mean curve; that the few points in 1929 follow the mean curve very well; and that in 1930 the few points near velocity-minimum are above the curve, while after phase $0^d$ the observations fall in general below. It is regrettable that the observations in the different seasons are not better distributed for this test; but as far as the evidence goes, it suggests that both the velocity of the center of mass and the shape of the velocity-curve undergo changes from season to season. In addition to these changes a few velocities stand off from others obtained during the same season. These may of course be the result of errors in the plates, but they may also be caused by short-period fluctuations in velocity superposed on the 75-day curve. As a large number of spectrograms judiciously placed would be required to settle whether irregularities such as these are real, it is necessary to confine the present discussion to the mean curves which seem best fitted to represent the measured velocities.

Both Figures 1*c* and 1*d* show double maxima and minima in a single light-period the phases of which are in fair agreement. The velocities for these four points on the two curves, together with the corresponding phases and those of the nearest minima and maxima on Waterfield's light-curve, are given in Table IV.

The last line shows the phase difference between these points for the light- and velocity-curves. With the exception of the last value, which depends on the least easily determined phase in the velocity-curves, the relation between velocity-maxima and light-minima and vice versa is fairly definite. The close relationship of velocity-maximum with light-minimum and vice versa for Cepheid variables is well known. The velocity-minima for AC Herculis follow the light-maxima by 10 and 7 days, respectively, and primary light-minimum

is followed in 6 days by a velocity-maximum. The evidence seems to favor the assumption of a Cepheid-like relation between the two

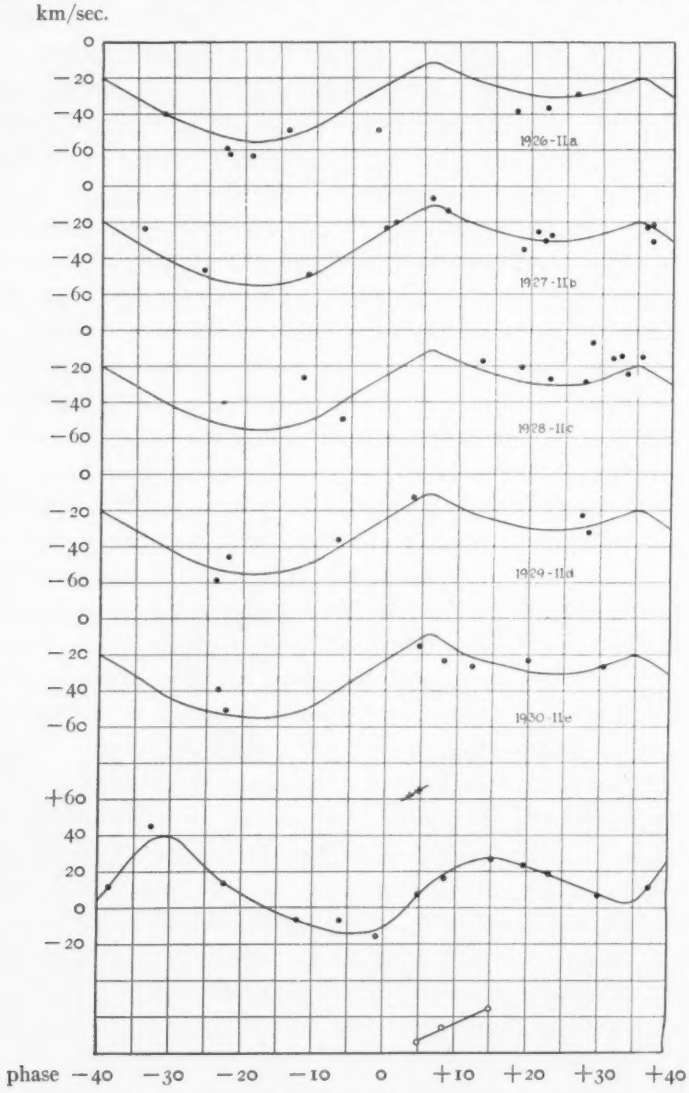



FIG. 2.—Curves *a* to *e* show the plot of the arc-line velocities for each observing season 1926–1930 and the mean velocity-curve for the arc lines (solid line in 1*c*). At the bottom are plotted the differences, hydrogen-line minus arc-line velocities for the red emission components (crosses), the absorption components (dots), and the violet components (circles).

curves with a time lag of about 7 days for the velocity-curve, although the last difference is opposite in sign to the other three.

The mean radial velocity may be determined with about equal weight in either of two ways: (1) by determining the velocity which divides the curves into two equal areas—the result for the arc-line curve is −32.8 km/sec.; for the enhanced-line curve, −25.0 km/sec.; (2) by forming the simple means of the radial velocities, which may be done since the observations are well distributed over all phases. These results are −31.0 and −25.0 km/sec., respectively. The values adopted are the means of the determinations, viz., −31.9 and −25.0 km/sec.

TABLE IV

| | Pri. Vel. Min. | Pri. Vel. Max. | Sec. Vel. Min. | Sec. Vel. Max. |
|---|---|---|---|---|
| Enhanced lines | −52 km/sec. | − 8 km/sec. | −26 km/sec. | −10 km/sec. |
| Arc lines | −57.5 | −11 | −30.5 | −21 |
| Diff. (Enh.−Arc) | + 5.5 | + 3 | + 4.5 | +11 |
| Phase | −18 days | + 6 days | +25 days | +34 days |
| Nearest extremes in Waterfield's light-curve | Sec. max. | Pri. min. | Pri. max. | Sec. min. |
| Phase of preceding | −28 days | 0 days | +18 days | +37.5 days |
| Difference in phase of velocity and light extremes | +10 | + 6 | + 7 | − 3.5 |

The difference between the two means (Enhanced−Arc = +6.9 km/sec.) has the same sign as that found for other stars from measurements on large-scale spectrograms. Adams[1] obtained for Sirius, Procyon, and Arcturus the differences +0.90, +0.58, and +0.08 km/sec., respectively. Blends may be responsible for some of the difference found for AC Herculis, but it is unlikely that they account for all of it, since for a considerable number of lines their effect should in the long run be as often in one direction as the other. The enhanced lines therefore give an algebraically larger velocity than the arc lines; but the difference is not necessarily as large as +6.9 km/sec. Table IV shows that the value at velocity maximum is +1.5 km/sec. as against +7.5 km/sec. for the mean difference for the other three points. The part of the velocity-curve which is most

[1] *Mt. Wilson Contr.*, No. 50; *Astrophysical Journal*, **33**, 64, 1911.

closely associated with maximum light and early spectral type gives a larger difference than that for the point most closely associated with minimum light or late spectral class. It must be noted, however, that the phase of the last-mentioned difference, $6^d$, is well advanced toward primary light-maximum or early type. Moreover, it should

TABLE V

VELOCITY DIFFERENCE BETWEEN VIOLET EMISSION HYDROGEN LINES AND ARC LINES

| Approx. Phase | Velocity Diff. |
|---|---|
| $4^d9$ | −74 km/sec. |
| 8.3 | 66 |
| 13.8 | −56 |

TABLE VI

VELOCITY DIFFERENCE BETWEEN HYDROGEN ABSORPTION LINES AND ARC LINES

| No. | Approx. Phase | Velocity Difference |
|---|---|---|
| 1 | $4^d9$ | + 6.1 km/sec. |
| 2 | 7.3 | +13.4 |
| 3 | 15.0 | +28.8 |
| 4 | 19.4 | +23.5 |
| 5 | 22.9 | +18.9 |
| 6 | 30.0 | + 7.6 |
| 7 | 37.1 | +11.6 |
| 8 | 42.8 | +35.8 |
| 9 | 53.1 | +13.6 |
| 10 | 63.3 | − 6.4 |
| 11 | 69.3 | − 6.5 |
| 12 | 74.4 | −15.6 |

be recognized that the change with phase in the difference between enhanced and arc-line velocities depends much upon the judgment shown in drawing the respective mean velocity-curves.

The radial velocities from the hydrogen lines $H\delta$, $H\gamma$, and $H\beta$ deserve special mention. The general changes which these lines undergo have already been described. It is of interest and perhaps sheds some light upon their behavior to present the deviations of the radial velocities of both emission and absorption hydrogen lines from the velocities of the arc lines. These data are given for each plate in

Table III. The individual deviations are of relatively low weight on account of the few hydrogen lines available, and, therefore, mean values were formed by weighting the plates according to the number of hydrogen lines involved. The two spectrograms C 5441 and $\gamma$ 15174, which show measurable red and violet emission components, gave, for the red emission, displacements of +63 and +68 km/sec., respectively. The velocity differences for the violet components measured on eleven spectrograms give the three normal places in Table V. The absorption lines of hydrogen furnish the mean differences referred to arc lines which appear in Table VI.

These values have been plotted at the bottom of Figure 2, in which the crosses denote the differences between the velocities from the red emission components and the corresponding arc-line velocities; the circles, these same differences for the absorption lines; and dots, those for the violet emission components. The two values for the red components are insufficient to establish with certainty the rate of change which this difference undergoes in the short phase interval involved, although it is interesting to note that the change is upward. The slope of the differences for the violet component should have considerable weight. The three values show a consistent rapid trend upward. The differences for the absorption lines are represented by a curve having two maxima and two minima, the departures from which for individual normal places are not at all serious.

The differences from the arc-line velocities trend rapidly upward for all three classes of lines wherever the data are complete. Apparently the absorption lines are affected by the adjacent emissions, a result further confirmed by the continued general parallelism of the slopes of the differences for the violet components with those of the differences for the absorption lines. It appears from the description already given of the behavior of the emission borders that the red component undergoes a rapid diminution in strength relative to the violet component during the interval that emission is discernible. It is therefore quite probable that the rapid increase noted in the red shift of the absorption lines of hydrogen is caused both by an actual trend of the emission borders toward the red and by a weakening of the red as compared to the violet component of emission.

The ordinates at the bottom of Figure 2 express, in kilometers per second, the displacement of the absorption lines of hydrogen relative to the arc lines as it depends upon phase. The shift is to the red if the ordinate is positive, to the violet if it is negative. Evidently the greater of the two maxima is closely associated with secondary and the other with primary light-maximum. The primary minimum of this curve is associated with primary light-minimum and its secondary minimum with secondary light-minimum. Indeed, if the phases of this curve are increased by approximately 4 days, it strongly resembles the light-curve. The parts of the curve with zero ordinates belong to phases at which the absorption lines of hydrogen give the same velocities as the arc lines. These phases are evidently 64, 3, and 34 days. The greatest red-shifts are at phases 45 and 15 days. From 64 to 3 days the curve shows evidence of a slight violet-shift. It is to be remembered, in this connection, that, when evidence of emission first appears close to minimum light, the red component seems to be the stronger.

The most rapid changes in the last curve of Figure 2 are on its ascending branches and coincide with the rapid rises in the light-curve toward its maxima. The greatest red-shift occurs at the phases when emission is most conspicuous.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
January 1931

# THE SPECTROHELIOSCOPE AND ITS WORK[1]

## PART III. SOLAR ERUPTIONS AND THEIR APPARENT TERRESTRIAL EFFECTS

By GEORGE E. HALE

ABSTRACT

In co-operative observations with the spectrohelioscope, to be made at many stations distributed around the world, occasional violent eruptions on the sun's disk call for first attention. Many of these phenomena are described and illustrated in this paper. Most of them were photographed with the spectroheliographs of the Kenwood, Yerkes, Mount Wilson, South Kensington, Kodaikanal, and Meudon Observatories, which should be used in connection with the chain of spectrohelioscopes for their detection and study.

Several of these eruptions were followed after an (average) interval of about twenty-six hours by violent terrestrial magnetic storms and brilliant auroras. The principal theories of these phenomena, all of which ascribe them to the influence of solar disturbances, are briefly outlined.

The paper includes a list of the 23 widely distributed observatories where spectrohelioscopes are already in use or will soon be erected. Other spectrohelioscopes will be available later at additional stations. It will thus be possible to inaugurate a comprehensive series of observations under the auspices of the International Astronomical Union.

In previous papers of this series I have described the spectrohelioscope and its adjustments and have given a few observations of the hydrogen flocculi near sun-spots made with its aid.[2] Deferring for the present further discussion of other similar observations, I have thought it advisable to devote the present paper to an account of some exceptional outbursts on the sun's disk, most of which have been followed by brilliant auroras and widespread magnetic storms. Although certain important discrepancies remain unexplained, the evidence seems to favor the view that the observed solar eruptions are directly connected with these terrestrial phenomena.

The spectrohelioscope and the spectroheliograph easily reveal in the light of hydrogen or calcium the sudden appearance and the rapidly changing forms of eruptions on the sun's disk. As these outbursts may not last more than a few minutes, an adequate chain

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 425.

[2] Part I: "History, Instruments, Adjustments, and Methods of Observation," *Mt. Wilson Contr.*, No. 388; *Astrophysical Journal*, **70**, 265, 1929; Part II: "The Motions of the Hydrogen Flocculi near Sun-Spots," *Mt. Wilson Contr.*, No. 393; *Astrophysical Journal*, **71**, 73, 1930.

of instruments, distributed around the earth and used in a co-operative plan, is needed to make the solar record sufficiently complete for comparison with records of the various terrestrial phenomena in question. During the last few years twenty-three spectrohelioscopes and coelostat telescopes of the type described in the first paper of this series have been built or ordered for the observatories listed on page 411, and others will soon be added. It is therefore evident that a fairly comprehensive co-operative observational scheme is now feasible.

It is important that all signs of eruption on the disk, especially those observed near the central meridian of the sun, be followed and carefully analyzed. Many small eruptions may break out suddenly and subside within a short time, but others, of similar appearance in their initial stages, may develop into vast outbursts, of intense brilliancy and of great importance from a geophysical standpoint. If, as the available evidence so strongly suggests, rapid changes in intense flocculi near the central meridian of the sun are usually followed by terrestrial disturbances, it is highly desirable that all the significant facts, such as their times of appearance, maximum development, and disappearance, and their approximate heliographic position, form, area, motions, and intensity at successive stages, be learned as soon as possible. The various theories hitherto proposed, especially those which attribute to radiation pressure the flight of erupted gases from the sun to the earth, can then be thoroughly tested, thus greatly facilitating other studies of solar and terrestrial relationship. Existing data are very incomplete, as might be expected because of the small number of observations made daily and the distribution of properly equipped observers in longitude. The spectrohelioscopes now available are more numerous, better distributed in longitude, and much quicker in action than the few spectroheliographs in daily use. They also have the advantage of permitting the instant change in wave-length of the light under observation, thus enabling effects often missed with the spectroheliograph to be detected and analyzed. By means of a simple attachment, to be described in a later paper, they can be quickly adapted for photographically recording unusual phenomena in light of any wave-length.

Although accounts of many of the solar eruptions described in the following pages have been published, they are scattered through English, American, and French journals, covering a period of nearly seventy years, and are therefore often overlooked by physicists, geophysicists, and even by astronomers interested in widely different observational or theoretical aspects of the subject. The original papers should always be consulted when available, but an illustrated summary may be useful in calling attention to the further possibilities of research.

### "A SINGULAR APPEARANCE SEEN IN THE SUN ON SEPTEMBER 1, 1859"

Carrington's classic volume, *Observations of the Spots on the Sun* (London, 1863), refers on page 167 to a remarkable observation lasting about five minutes which he described and illustrated in the *Monthly Notices of the Royal Astronomical Society*, **20**, 13, 1859. While making his daily record of the forms and positions of sunspots on September 1, 1859,

> within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram (Fig. 1) by the letters *A* and *B*, and of the forms of the spaces left white. My first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by which the general image is thrown into shade, for the brilliancy was fully equal to that of direct sun-light; but, by at once interrupting the current observation, and causing the image to move by turning the R.A. handle, I saw I was an unprepared witness of a very different affair. I thereupon noted down the time by the chronometer, and seeing the outburst to be very rapidly on the increase, and being somewhat flurried by the surprise, I hastily ran to call some one to witness the exhibition with me, and on returning within 60 seconds, was mortified to find that it was already much changed and enfeebled. Very shortly afterwards the last trace was gone, and although I maintained a strict watch for nearly an hour, no recurrence took place. The last traces were at *C* and *D*, the patches having travelled considerably from their first position and vanishing as two rapidly fading dots of white light. The instant of the first outburst was not 15 seconds different from $11^h18^m$ Greenwich mean time, and $11^h23^m$ was taken for the time of disappearance. In this lapse of 5 minutes, the two patches of light traversed a space of about 35,000 miles, as may be seen by the diagram, which is given exactly on a scale of 12 inches to the sun's diameter. On this scale the section of the earth will be very nearly equal in area to that of the detached spot situated most to the north in

the diagram, and the section of *Jupiter* would about cover the area of the larger group, without including the outlying portions. It was impossible, on first witnessing an appearance so similar to a sudden conflagration, not to expect a considerable result in the way of alteration of the details of the group in which it occurred; and I was certainly surprised, on referring to the sketch which I had carefully and satisfactorily (and I may add fortunately) finished before the occurrence, at finding myself unable to recognize any change whatever as having taken place. The impression left upon me is, that the phenomenon took place at an elevation considerably above the general surface of the sun, and, accordingly, altogether above and over the great group in which it was seen projected.

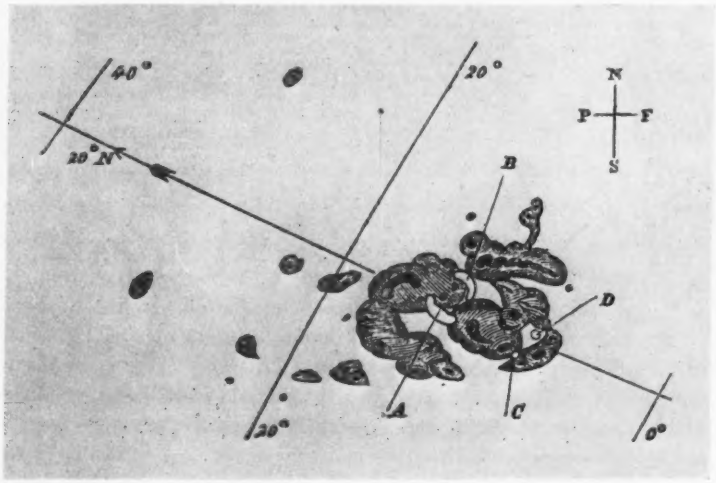



FIG. 1.—September 1, 1859, $11^h18^m$ G.M.T.; sun's diameter = 289 mm (Carrington)

Both in figure and position the patches of light seemed entirely independent of the configuration of the great spot, and of its parts, whether nucleus or umbra.

[Mr. Carrington exhibited at the November Meeting of the Society a complete diagram of the disk of the sun at the time, and copies of the photographic records of the variations of the three magnetic elements, as obtained at Kew, and pointed out that a moderate but very marked disturbance took place at about $11^h20^m$ A.M., Sept. 1st, of short duration; and that towards four hours after midnight there commenced a great magnetic storm, which subsequent accounts established to have been as considerable in the southern as in the northern hemisphere. While the contemporary occurrence may deserve noting, he would not have it supposed that he even leans towards hastily connecting them. "One swallow does not make a summer."]

Hodgson, who fortunately observed this phenomenon, describes it in the same number of the *Monthly Notices* (p. 15) as follows:

While observing a group of solar spots on the 1st September, I was suddenly surprised at the appearance of a very brilliant star of light, much brighter than the sun's surface, most dazzling to the protected eye, illuminating the upper edges of the adjacent spots and streaks, not unlike in effect the edging of the clouds at sunset; the rays extended in all directions; and the center might be compared to the dazzling brilliancy of the bright star *α Lyrae* when seen in a large telescope with low power. It lasted for some five minutes, and disappeared instantaneously about 11:25 A.M.

The magnetic storm referred to by Carrington was described by Balfour Stewart,[1] who remarked on "its excessive violence and length of duration" and the accompanying "auroral displays of almost unprecedented magnificence," observed in Europe, America (as far south as Cuba), and Australia. From an analysis of the photographic magnetic records obtained at the Kew Observatory,

it appears that we have two distinct well-marked disturbances, each commencing abruptly and ending gradually, the first of which began on the evening of August 28, and the second on the early morning [5:00 A.M.] of September 2. These two great disturbances correspond therefore in point of time to the two great auroral displays already alluded to.

After describing these magnetic phenomena he adds:

But, besides these two remarkable disturbances into which it divides itself, this great storm comprehends a minor disturbance, not approaching these two in extent, but yet possessing an interest peculiar in itself, which entitles it to be mentioned. . . . . This disturbance occurred as nearly as possible at $11^h15^m$ A.M. Greenwich mean time, on September 1, 1859, affecting all the elements simultaneously, and commencing quite abruptly.

After quoting the greater part of Carrington's paper and referring to the conclusions of Sabine regarding the relationship between sunspots, auroras, earth currents, and magnetic disturbances, Stewart suggests that the terrestrial effects are due to sudden variations in the intensity of a primary current in the sun, which induce secondary currents along the surface of the earth and the upper strata of the atmosphere. The question was thus raised whether Carrington's phenomenon was directly responsible for a small instantaneous effect on the earth's magnetic field, or for the much greater magnetic disturbance that began nearly eighteen hours later and corresponded in time to one of the two brilliant auroral displays.

[1] *Philosophical Transactions of the Royal Society of London*, **151**, 423, 1861.

Professor Young's preference for a direct electromagnetic action on the earth, propagated with the velocity of light, of every intense solar disturbance was partly due to his experience at Mount Sherman in 1872, where he observed several brilliant distortions of the *Ha* line near a sun-spot at the sun's eastern limb that closely coincided in time with "peculiar twitches of the magnets in England." With characteristic caution, however, he quoted Lord Kelvin's conclusion (1892) against the possibility of such magnetic action of the sun and added:

> Of course, as has been said, no two or three coincidences such as have been adduced are sufficient to establish the doctrine of the sun's immediate magnetic action upon the earth, but they make it so far probable as to warrant a careful investigation of the matter—an investigation, however, which is not easy, since it implies a practically continuous watch of the solar surface.[1]

Speaking of the well-known but still obscure parallelism between curves of magnetic intensity and auroral and sun-spot frequency, he also acutely remarked, many years before the discovery of radiation pressure, that perhaps the solar effect is "in some way kindred with the action which drives off the material of a comet's tail, and proves that other forces besides gravitation are operative in interplanetary space."[2]

## THE SOLAR ERUPTION OF JULY 15, 1892

My own experience in this field began on July 15, 1892, when a series of photographs of a remarkable solar disturbance was obtained with the recently mounted spectroheliograph of the Kenwood Observatory, Chicago.[3] The scene of the disturbance was a large and active sun-spot, which had first appeared as a few small dots at about 32° south latitude on June 13, during the previous rotation. On July 8 it had returned to the east limb of the sun, and on July 15 it was near the central meridian.

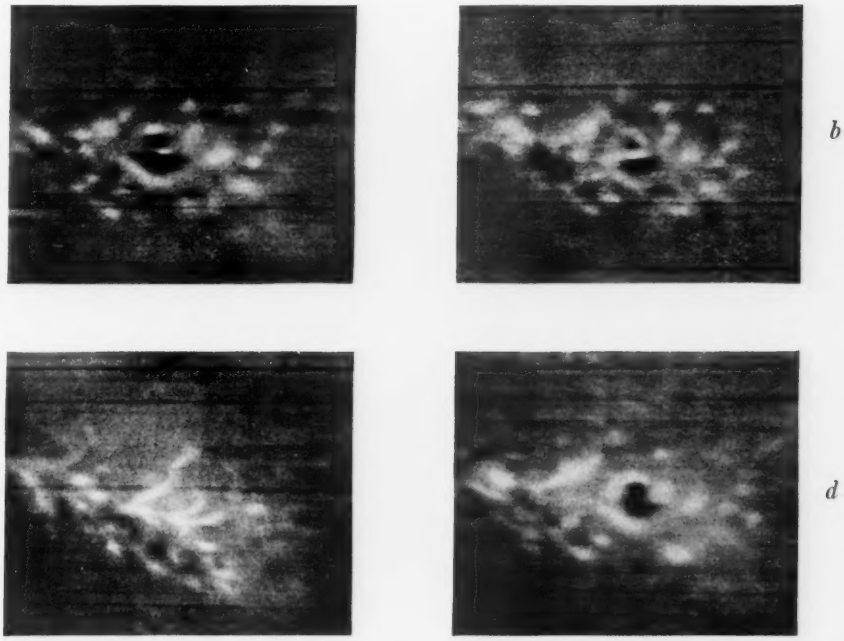
The first photograph, taken with the calcium (K) line at about $16^h58^m$ G.C.T. (Plate IV*a*), showed nothing unusual, except that the bridge between the northern and southern umbrae of the spot was

[1] *The Sun* (rev. ed.), pp. 166–169, 1895.

[2] *Ibid.* (2d ed.), p. 156, 1884.

[3] Hale, "A Remarkable Solar Disturbance," *Astronomy and Astrophysics*, 11, 611, 1892.

PLATE IV




Solar eruption of July 15, 1892, photographed with the calcium line $K_2$; sun's diameter = 207 mm (Kenwood Observatory): *a*, $16^h58^m$; *b*, $17^h10^m$; *c*, $17^h37^m$; *d*, $19^h50^m$ G.C.T.

brighter than usual. The next exposure, made about twelve minutes later, showed a very different state of affairs. Extending between the umbrae, in a direction slightly inclined to the sun's equator, was a perfectly straight and exceedingly brilliant object, which expanded slightly at its eastern extremity and turned sharply toward the north, terminating abruptly in a brilliant ball just east of the center of the northern umbra. The sudden formation of this remarkable object did not seem to affect the spot or the general group of flocculi surrounding it, which showed no material change of form. As the plates were not developed immediately, the occurrence of the eruption was not known at once, and the next photograph was not taken until about $17^h37^m$ G.C.T. Meanwhile, an entire transformation had taken place in the luminous phenomenon, which now completely covered the spot and a large area surrounding it. About an hour later I observed the *Hα* line visually in the spectrum of the spot and found, at some distance to the west of the group, that the reversals were so brilliant that the form of the hydrogen cloud could be very well seen through a widely opened slit. Spectra of various parts of the spot photographed at $19^h$ and spectroheliograms taken at $19^h31^m$ and $19^h40^m$ G.C.T. showed the flocculi surrounding the spot to be of the same form as before the disturbance, which had then completely disappeared. It therefore began at about $16^h58^m$, reached the greatest recorded stage of its development in about $39^m$, and vanished about two hours after its first appearance.

I am indebted to Mr. J. A. Fleming, acting director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, for copies of magnetograms showing the magnetic storms associated with many of the solar phenomena described in this paper. Those for July, 1892, which are from the records of the Royal Observatory, Greenwich, show marked disturbances on July 12, 14, and 17, and a much greater one on July 16. The latter commenced suddenly shortly after noon (about $12^h30^m$) on July 16, and continued with somewhat reduced amplitudes until about $17^h30^m$; a violent series of deflections then began, continuing with varying intensity until about $19^h8^m$, when another violent disturbance began and lasted nearly forty minutes. The storm then suddenly moderated, although marked but less violent deflections occurred later.

The sudden beginning at about $12^h30^m$ was approximately nineteen and a half hours after the first of the Kenwood exposures, but the interval between this first spectroheliogram and the beginning of the violent magnetic storm at $17^h30^m$ was about twenty-four and a half hours. Further details regarding the various phenomena photographed with the Kenwood spectroheliograph near this and other spot groups in June and July; Rudaux's direct observations of the eruption of July 15; my own observations of a brilliant aurora on the evening of July 16; Townsend's visual spectroscopic observations of the same spot on various dates; and Sidgreaves' account of the July solar disturbances and magnetic storms—all may be found in the papers cited below.[1] The chief points suggested by these observations are as follows:

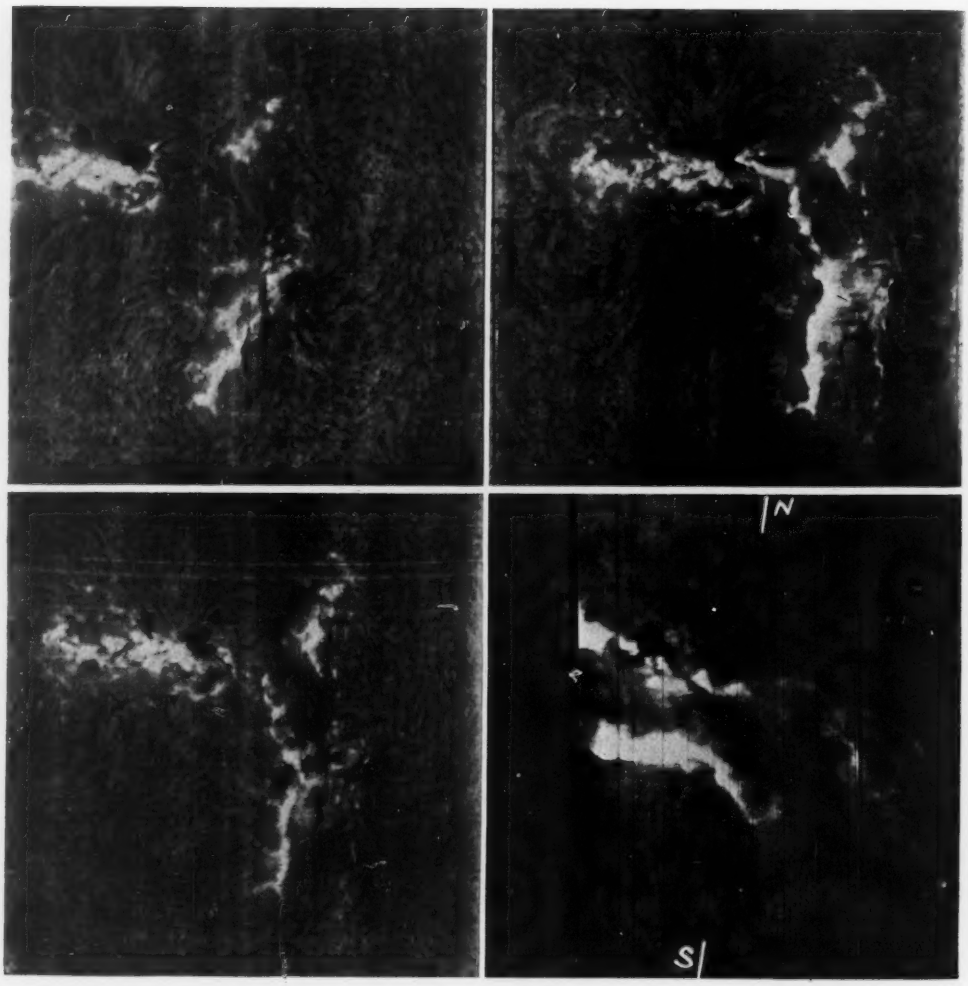
1. Eruptions on the sun's disk apparently associated with magnetic storms are characterized by increased intensity of the $Ca^+$ and hydrogen lines, and may therefore be observed spectroscopically or photographed with the spectroheliograph.

2. Sidgreaves remarked that "on the 11th, the day Mr. Townsend observed the remarkable reversals of the C ($H\alpha$) line over the spot at about $12^h15^m$ P.M., G.M.T., a single sharp upward movement both on the declination and horizontal force magnets alone interrupted their otherwise quiescent state." At the time of my own observation of July 15, according to Sidgreaves, "there was not the slightest disturbance on the vertical force and declination magnets. There was, however, a slight trembling in the horizontal force magnet," but the actual magnetic storm did not begin until the following day. On the whole, the hypothesis that the effect of a violent solar eruption is transmitted to the earth with the velocity of light received little or no support from these observations.

3. The occurrence of a terrestrial magnetic storm about nineteen and a half hours after the beginning of the solar eruption and a much more violent storm about five hours later may be compared with

[1] Hale, "On the Condition of the Sun's Surface in June and July, 1892, as Compared with the Record of Terrestrial Magnetism," *ibid.*, p. 917; "Magnetic Disturbances and Auroras," *ibid.*, p. 617; Townsend, "The Solar Disturbance of July, 1892," *ibid.*, p. 815; Sidgreaves, "The Solar Disturbance of July, 1892, and the Accompanying Magnetic Storms," *ibid.*, p. 819.

PLATE V




*a*, *b*, *c*.—Solar eruption of September 10, 1908, photographed with the hydrogen line *Hα*, at $5^h36^m$, $8^h25^m$, and $9^h48^m$ G.M.T., respectively; sun's diameter = 168 mm (Yerkes Observatory).

*d*.—Eruption of May 12, 1909, photographed with *Hα* at $14^h45^m$ G.C.T.; sun's diameter = 226 mm (Mount Wilson Observatory).

the interval of about $17^h42^m$ between the apparent solar and terrestrial effects noted in Carrington's case, though the latter value might have been greater if his observations had been made with calcium or hydrogen light.

4. Another resemblance with Carrington's observation lies in the fact that both spots in which the outbursts occurred were near the central meridian of the sun.

5. Still another agreement with Carrington is the absence of any change in the spot after the eruption, which led me to infer, in the first paper cited, that "we seem to be dealing with an extremely brilliant eruptive prominence."

6. On this assumption, the visibility of Carrington's outburst in the white light of the direct solar image may be ascribed to the presence in the prominence of a very bright continuous spectrum, such as has often been observed in brilliant eruptive prominences at the sun's limb.

7. It should be added, however, that either through lack of observations or for some other cause no solar outburst corresponding to that of July 15 is known to account for the other magnetic storms recorded in July, 1892, at Greenwich.

8. Sidgreaves, noting that three magnetic storms coincided with three separate meridian passages of the same spot, remarked that this "only serves to confirm the opinion expressed in the *Stonyhurst College Observatory Report* for 1883 that 'there is some evidence to show that the aurorae and magnetic storms synchronize rather with particular classes of spots than with solar disturbances generally.' "

### THE ERUPTION OF SEPTEMBER 10, 1908

This important eruption (Plate V), which extended across the solar equator so as to connect two large spots in the northern and southern hemispheres, was photographed in most of its phases by Messrs. Fox and Abetti with the Rumford spectroheliograph of the Yerkes Observatory.[1]

The first plates of September 10 were the routine calcium exposures. These showed considerable activity in the spot groups, principally in the eruptions in

[1] "Interaction of Sun-Spots," *Astrophysical Journal*, **29**, 42, 44, 1909.

the northern group. The *Hα* plates of $5^h36^m$ and $5^h58^m$ G.M.T. revealed an intensification of the eruptions in the northern group,[1] a brightening of the flocculi following the southern group, and a slight strengthening of the isolated flocculus preceding the northern group, but gave no intimation of the pending outburst. Visual, spectroscopic examination at $7^h30^m$ G.M.T. indicated a violent uprush of hydrogen immediately behind the southern spot and also at some distance following. A plate was immediately exposed, $7^h52^m$. On this and subsequent plates tremendous changes were found. A brilliant eruption had occurred behind and in contact with the southern spot. Somewhat more remotely following, a still greater and more striking eruption was in progress, extending east and south like a great leg, brilliant to its toe, and stretching to the north in two branches, one nearly to the neighboring spot, the other a chain of brilliant eruptions reaching toward the isolated flocculus. This flocculus, the remains of an expired spot, had increased greatly in intensity and had extended arms toward the approaching chain of eruptions and toward the northern spot. From the northern spot an eruptive arm stretched to meet the eruptions advancing from below and from the flocculus. This is well seen at $8^h13^m$. At $8^h25^m$ the connection of the northern and southern spots was completed.

After this consummation the subsidence to relative tranquillity was as rapid as the rise. Examination of the line *Hα* at $9^h30^m$ revealed descent in the eruptive regions behind the southern spot. Measurement of the displacement of the line on the photographs made at this time gives velocity of descent behind the spot as about 100 km per second and 170 km in the great eruption due east of the spot. The result of this is seen on the plates at $9^h39^m$ and $9^h48^m$ in the obliteration of the eruptive feature behind the spot and in the decline in the great eruption. Other plates exposed later showed a continued decline. The whole display lasted less than four hours and fortunately the history of it as shown on our plates is nearly complete. . . . .

Several investigators have expressed the opinion that the source of terrestrial magnetic storms is in the eruptions about the spots rather than in the spots themselves. Hale in discussing the magnetic fields which he has recently detected in sun-spots concludes, from the rapid diminution of strength of field with altitude, that terrestrial magnetic storms are probably not caused directly by these fields[2] and states: "Their origin may be sought with more hope of success in the eruptions shown on spectroheliograph plates in the regions surrounding spots." A disturbance of the magnitude of this one of September 10 might have been expected to produce noticeable effects on the earth. In *Nature* of September 24 Chree describes a large magnetic storm which occurred on September 11, beginning at $9^h47^m$. The lag in time between the solar and terrestrial storms, something over twenty-six hours, is not consistent with the view of Young[3] and of Nordmann[4] that the magnetic impulse travels with the speed of light; but is more in harmony with the observations of Maunder[5] and of Riccò,[6] who find retardations of $26^h$ and $45^h.5$ respectively. The lags found by Maunder and Riccò, though both rest on the central meridian passage of sun-spots, are not

directly comparable, for Maunder determined the lag to the middle of the magnetic storm and Riccò to the maximum.

[1] Dennett observed an eruption in this group on September 9 lasting from $19^h45$ to $20^h30$ G.M.T. (*Observatory*, **31**, 388, 1908).

[2] *Astrophysical Journal*, **28**, 341, 1908; see also Schuster, *Nature*, **78**, 663, 1908; *Monthly Notices of the Royal Astronomical Society*, **65**, 187, 1904.

[3] *Nature*, **7**, 109, 1872.

[4] *Journal de Physique* (4), **3**, 115, 1904.

[5] *Monthly Notices of the Royal Astronomical Society*, **64**, 207, 1903–1904.

[6] *Memorie della Società degli Spectroscopisti Italiani*, **33**, 38, 1904.

The Greenwich magnetograms for this storm show a sudden beginning, as stated by Chree, on September 11 at $9^h47^m$, G.M.T. Great deflections occurred between midnight and about 8:00 A.M. on September 12.

The conclusions of Maunder and Riccò refer, not to such eruptions as are described in this article, but to large sun-spots. From an extensive statistical investigation of the relationship between sun-spots and terrestrial magnetic storms, Maunder found that such storms begin during a period of from thirty-four hours before to eighty-six hours after the passage of a group of spots across the central meridian of the sun. The mean time of the beginning of a magnetic storm is twenty-six hours after that of central meridian transit.[1] Maunder pointed out in 1892, however, that while in many cases terrestrial magnetic storms are undoubtedly connected with large sun-spots,

> spots as important have been seen upon the sun, and the magnets have scarcely fluttered, and storms as distinct have occurred when there have been only few spots, and those but small, upon the visible disk of the sun. . . . . The conclusion to my own mind seems to be that though Sun-spots are the particular solar phenomena most easily observed, we must not infer therefore that their number and extent afford the truest indications of the changes in the solar activity which produce the perturbations we remark in our magnetic needles.[2]

Moreover, in a letter dated March 17, 1892, Tacchini wrote me from Rome regarding the Kenwood spectroheliograph:

> Comme j'ai noté dans le dernier numéro des *Memorie*, j'ai montré autrefois, qu'avec plus de probabilité, ce sont les phénomènes chromosphériques et ceux qui se produisent dans l'atmosphère du Soleil, qui correspondent aux phénomènes magnétiques terrestres; de maniére que, si une tache passe sur le

[1] *Monthly Notices of the Royal Astronomical Society*, **64**, 205, 1904, and **65**, 2, 1904.

[2] Quoted from *Knowledge* in *Astronomy and Astrophysics*, **11**, 528, 1892.

disque dans un état de calme, nous n'aurons pas des aurores ni des perturbations magnétiques correspondantes; au contraire, si un jour sur la tache ou sur les facules auront lieu des phénomènes extraordinaires, que nous ne pouvons pas constater avec les moyens employés jusqu'à présent, on aura encore sur la terre et sur les autres planètes des perturbations. Or c'est avec vos observations qu'on pourra vérifier si un groupe de taches ou de facules en traversant le disque, se maintient calme toujours, ou si dans un temps donné se sont manifestés des phénomènes extraordinaires.[1]

### THE ERUPTION OF MAY 12, 1909

One of the most striking cases of a large eruption on the sun's disk followed by an intense magnetic storm is shown on two *Hα* spectroheliograms taken by Ellerman with the 60-foot tower telescope at Mount Wilson on May 12, 1909. The large spot group with which it was associated (Greenwich 6668 and 6669, a return of Greenwich 6658), at about 15° south latitude, had been marked by two small but bright hydrogen eruptions when near the east limb on May 9, and continued to give further evidences of activity. The first *Hα* plate, taken on May 12 at $14^h35^m$ G.C.T., when the group was about 15° east of the central meridian, showed two very large and brilliant calcium flocculi, one partly overlying the largest spot of the group, the other, even more brilliant but not so long, nearer the preceding spot. A second *Hα* plate, taken ten minutes later, is reproduced as Plate V*d*. This shows several marked changes when compared with the earlier plate. Unfortunately no more *Hα* spectroheliograms were made that day, though the spot group continued to give evidence of definite but much less marked eruptive activity as it crossed the disk.

An intense magnetic storm began at Greenwich on May 14, at $4^h9$ G.C.T., or thirty-eight and three-tenths hours after our first spectroheliogram was taken on May 12. This disturbance, which lasted thirty-nine hours, was an exceptional one, classed at Greenwich as a "great" storm.

### THE ERUPTION OF SEPTEMBER 24, 1909

In a paper on "The Magnetic Storm of September 25, 1909, and the Associated Solar Disturbance"[2] Dr. W. J. S. Lockyer describes

[1] *Ibid.*, p. 437.

[2] *Monthly Notices of the Royal Astronomical Society*, **70**, 12, 1909.

and illustrates a series of calcium spectroheliograms, obtained at the South Kensington Observatory, of a large spot at south latitude 5°, which crossed the central meridian on September 23:

To continue and end the history of this group as recorded in calcium light we now come to September 24. On that day four photographs of the disc were secured, and no others were possible until October 5, in consequence of unfavorable weather.

*September* 24, $10^h5^m50^s$.—This photograph shows a complete transformation of the large flocculus group in comparison with those taken previously. The two most striking features are the great increase in intensity, and the nearly complete change of form. The flocculus group towards the south-west maintains its form and intensity, as exhibited on the 21st and 22nd, showing that the disturbed area was local to the other group. Special attention should be drawn to the great brilliancy of the calcium cloud in the north-western quadrant of the group, which seems to have the appearance of a portion of a spiral.

A photograph taken about five minutes later indicates definite changes of form and intensity, while photographs made at $11^h11^m$ and $11^h16^m$ show a marked reduction in the intensity and area of the bright flocculus recorded on the first plate. Of this Lockyer states:

The gradual crescendo of activity up to the 22nd, and the abrupt change in appearance of the group between $10^h10^m$ and $11^h11^m$ on the morning of the 24th, suggest that possibly 10 o'clock on the 24th might approximately represent the time of greatest activity.

The series of photographs here illustrated shows, I think, with little doubt, that we are, in photographs Nos. 5 and 6, in the presence of a large active prominence, situated above the ordinary solar level which produces the usual "$K_2$" flocculi.

An intense magnetic storm, described by Chree as probably not exceeded in range of the elements during the previous twenty years, was shown on the Kew records to begin at $11^h43^m$ A.M. on September 25, ending at $8^h30^m$ P.M. on the same day. According to Lockyer, Sidgreaves stated the storm to be at its height between $3^h30^m$ and $5^h30^m$ P.M. on the same date. Lockyer therefore took $4^h30^m$ P.M. as the approximate time of its greatest intensity, and gave twenty-five and three-quarters and thirty and a half hours, respectively, as the intervals between the maximum of the eruption and the beginning and the maximum of the magnetic storm.

The time of the beginning of this solar eruption is not exactly known, as it was in progress when Lockyer's first photograph was

taken on September 24, and no spectroheliograms were made at South Kensington on the previous day. Holmes observed a brilliant reversal of the *Hα* line in this spot at $11^h30^m$ G.C.T., on September 24, and this was also seen by Fowler (with open slit) at $12^h20^m$ on the same day. The Mount Wilson spectroheliograms made with the $H_2$ line of calcium on September 23, 24, and 25, and those made with the *Hα* line of hydrogen on September 24 and 25 show definite signs of activity in this spot group, but the eruption photographed by Lockyer was missed. Slocum, however, noted at the Yerkes Observatory that "the calcium flocculi over the spot present (on September 24) a marked spiral form, with several brilliant eruptions on the branches and outside the spiral." On the return of this spot in October he found it to be still active, with occasional small eruptions. Slocum also remarked that the spot was about 20° east of the central meridian when a brilliant auroral display was observed.[1] The magnetometer at Greenwich was "very active" on this date. Perhaps it should be added that while the magnetograms obtained at Lu-Kia-Pang, China, were incomplete (off the scale) during part of the storm, all three elements show the sharp beginning to be close to the time given by Chree, while the maximum range in declination occurred at about $13^h20^m$ G.C.T. on September 25.

### ERUPTIONS PHOTOGRAPHED IN JUNE, 1915

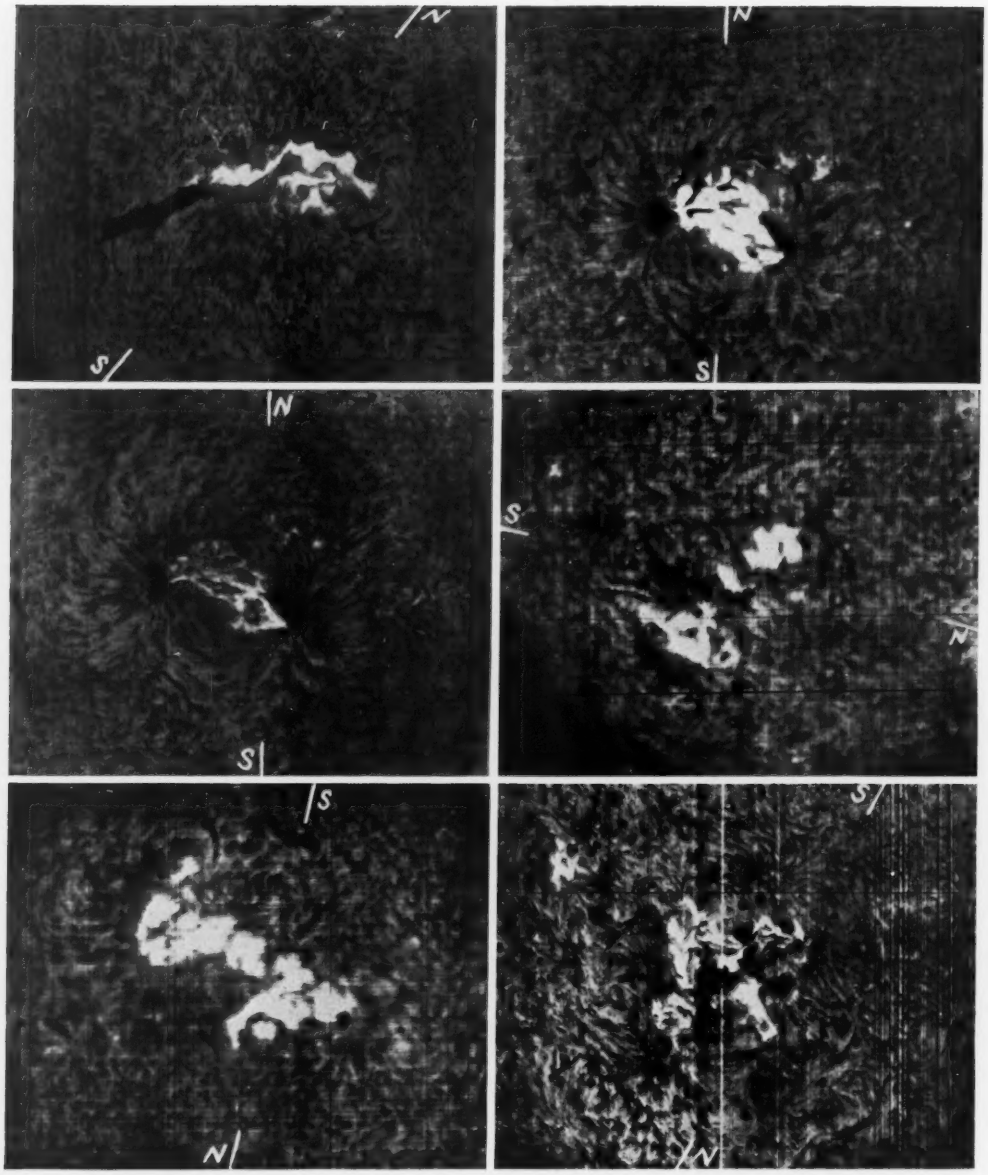
The Mount Wilson direct photographs of the sun indicate that between June 15, $15^h49^m$ and June 16, $14^h33^m$ G.C.T. a large spot suddenly developed in a very active group then east of the central meridian, which it crossed on June 18. This group (Greenwich 7299), at about 2° north latitude, showed many bright eruptions on our *Hα* spectroheliograms during its passage over the disk, but as none of these attained great size, it is impossible to connect any of them clearly with the intense magnetic storm[2] that began (Cheltenham Magnetic Observatory) at $13^h45^m$ G.C.T. on June 17 and continued about thirty-two hours.

Cortie had previously stated that both the activity and the heliographic latitude of a spot seem to determine its influence on terres-

[1] *Astrophysical Journal*, **31**, 26, 1910.

[2] *Journal of Terrestrial Magnetism*, **20**, 77, 1915.

## PLATE VI




Solar eruptions photographed with the hydrogen line *Hα*; sun's diameter = 169 mm (Mount Wilson Observatory).

*a*.—November 10, 1916, $15^h40^m$ G.C.T.
*b*.—February 7, 1917, $15^h59^m$ G.C.T.
*c*.—February 8, 1917, $15^h44^m$ G.C.T.
*d*.—February 14, 1917, $16^h6^m$ G.C.T.
*e*.—February 16, 1917, $15^h54^m$ G.C.T.
*f*.—August 8, 1917, $14^h23^m$ G.C.T.

trial magnetism.[1] Commenting on this particular group, with the Yerkes and Mount Wilson spectroheliograms before him, he remarked that "the conditions of great disturbance, and favorable position relatively to the earth, were both fulfilled." After noting the rapid changes in the group on June 16 and 18 and the eruptive activity shown by both sets of photographs, he emphasized the low latitude of the group, which corresponded almost exactly with the heliographic latitude of the earth, and added: "A violent magnetic storm, the greatest so far recorded during the present solar cycle, took place on June 17, which was accompanied by fine displays of Aurora Borealis in North America, and of Aurora Australis in New Zealand.[2]

It should be noted that other active spot groups, some of which showed minor eruptions, were on the sun's disk at this period. One of these, at about 17° north latitude (Greenwich 7304, June 15–27), which was of great size when it crossed the central meridian on June 21, showed a large bright flocculus connecting its preceding and following members on June 22, and other eruptive phenomena on June 23, 24, and 25. Another long stream at about 20° south latitude (Greenwich 7313, June 19–July 1) also showed marked signs of eruptive activity on some days, but not (on our plates) when near the central meridian.

### THE ERUPTION OF NOVEMBER 10, 1916

This eruption would have been especially well adapted for study with the spectrohelioscope if that instrument had then been available, because of the partial superposition of a large dark flocculus on the *Hα* spectroheliogram (Plate VI*a*). It was associated with the spot group Greenwich 7876 (November 6–17), at about 24° north latitude, which had appeared in two previous rotations as Greenwich 7833 and 7853. This group is described in the *Greenwich Photoheliographic Results* for 1916 as "a composite spot, *a*, with a close companion, *nf*, on November 6 to 8. Numerous small unstable spots form behind *a*, which diminishes but becomes more definite. The group is an irregular stream November 9–15, after which *a* alone

[1] *Monthly Notices of the Royal Astronomical Society*, **73**, 149, 1913.

[2] *Ibid.*, **76**, 17, 1915.

remains." The *Hα* spectroheliogram taken at Mount Wilson on November 10 at $15^h40^m$ G.C.T. shows the considerable area of the eruption, which was approximately 20° east of the central meridian. The long dark flocculus to the east was also shown in part on spectroheliograms taken November 8, 9, 11, and 13, but some of it might have been carried away from the sun by the eruption.

This outburst did not produce a great terrestrial magnetic storm,[1] though there were several minor magnetic disturbances during the month, one of them on November 10.

### THE ERUPTIONS OF FEBRUARY 7 AND 8, 1917

The large spot group at 16° south latitude (Greenwich 7977, February 3–16) increased greatly in size and changed rapidly in form as it advanced from the east limb, especially between February 4 and 8. *Hα* spectroheliograms taken at Mount Wilson by Ellerman on February 7 at $15^h59^m$ G.C.T., and on February 8 at $15^h44^m$ G.C.T., show the bright eruptions reproduced in Plate VI*b*, *c*.

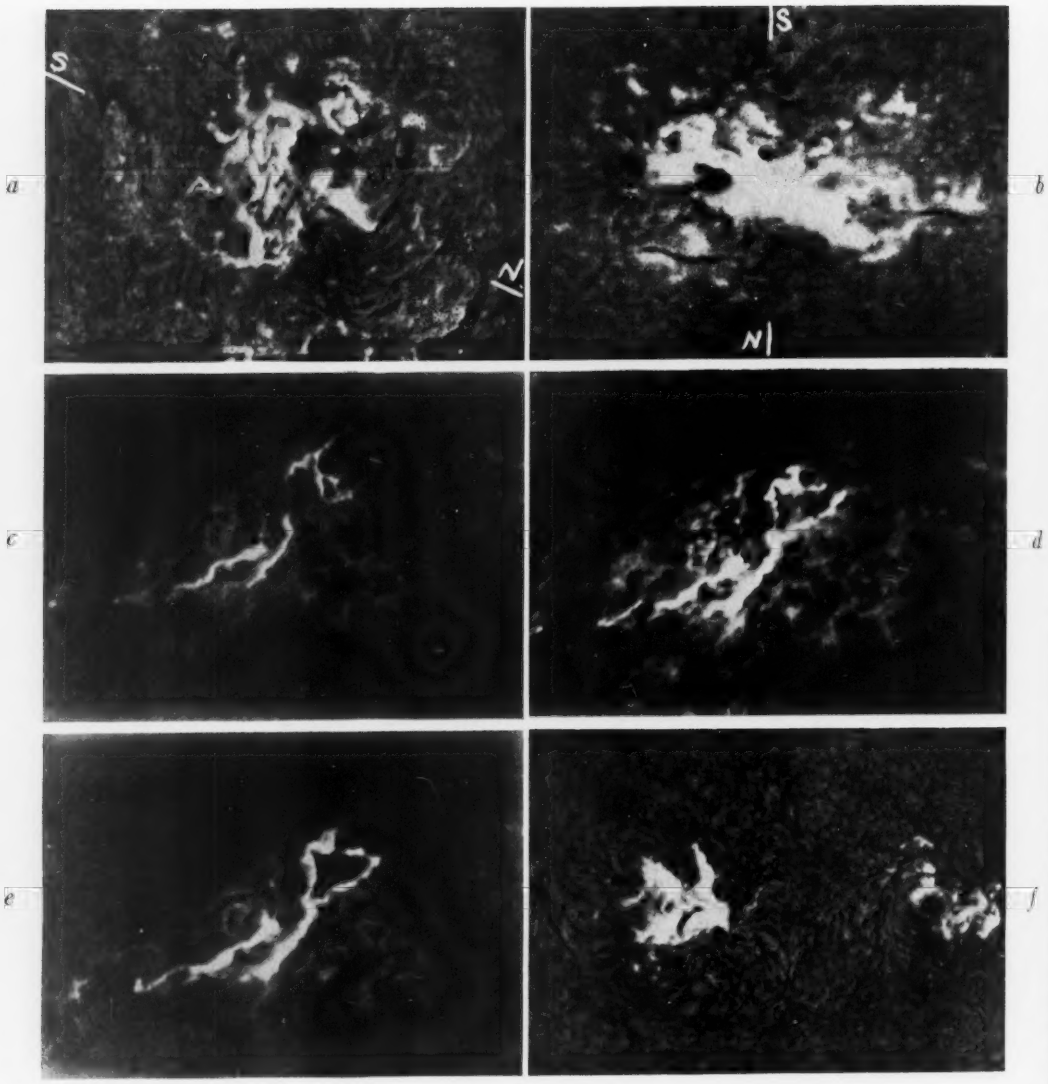
A moderate magnetic storm began at Greenwich on February 7 at $0^h$, with maximum from $22^h$ to $23^h15^m$. This was followed on February 8, between $17^h15^m$ and $19^h$, by another moderate storm, with other magnetic disturbances on February 14, 15, and 16. The incompleteness of our solar records renders it impossible to establish any reliable time interval between the solar and terrestrial phenomena. It should be noted, however, that the predominantly arched type of eruption indicated by the photographs suggests that most of the gases fell back upon the sun—a point that the use of a spectrohelioscope, or even a series of spectroscopic observations, might have cleared up.

### THE ERUPTIONS OF FEBRUARY 14 AND 16, 1917

On February 14 the above-mentioned spot group was near the west limb, but another smaller though active group at 23° south latitude had reached a point about halfway between the east limb and the central meridian. This was Greenwich 7986 (February 11–21), at about 23° south latitude. A diffuse eruption of moderate intensity is shown closely following the largest spot of this group on

[1] *Journal of Terrestrial Magnetism*, **22**, 50, 1917.

## PLATE VII




*a*, *b*.—Solar eruptions photographed at Mount Wilson August 9, 1917, $15^h13^m$, and January 24, 1926, $17^h34^m$, G.C.T., respectively; sun's diameter = 172 and 148 mm.

*c*, *d*, *e*.—Eruptions photographed at Kodaikanal February 22, 1926, at $8^h36^m$, $9^h0^m$, and $9^h4^m$, I.S.T., respectively; sun's diameter = 151 mm.

*f*.—Eruption photographed at Meudon October 13, 1926, at $13^h15^m$ G.C.T.; sun's diameter = 108 mm.

an *Hα* spectroheliogram taken at Mount Wilson by Nicholson on February 14 at $16^h6^m$ G.C.T. (Plate VI*d*).

Another eruption, somewhat brighter and larger, appears on an *Hα* plate taken on February 16 at $15^h54^m$ G.C.T. (Plate VI*e*). This also followed the leading spot, which had greatly increased in size and was about 13° east of the central meridian at the time of this second spectroheliogram. The weather was unsettled at this period and other spectroheliograms are not available.

There was a slight disturbance of the magnets at Greenwich on February 14 between $20^h15^m$ and $21^h45^m$, but a definite magnetic storm did not break out until February 15. This began at $12^h$ G.C.T., and lasted twenty-four hours, with its maximum at about $18^h$ on February 15. Less marked magnetic disturbances, in the form of irregular waves, were also recorded at Greenwich on February 17 from $19^h30^m$ to $20^h30^m$, August 18 from $0^h$ to $1^h$, and August 19 from $1^h45^m$ to $23^h$. It is thus difficult or impossible to fix an exact relationship between these solar and terrestrial phenomena. There was a time interval of about thirty hours between the moderate eruption of February 14 and the outbreak of the magnetic storm of February 15, and an interval of about thirty-five and a half hours between the somewhat brighter eruption of February 16 and the irregular wave (−22) in North Force on February 17, which was not classed among the "days of great disturbance."

### THE ERUPTIONS OF AUGUST, 1917

August, 1917, was an exceptionally disturbed month, both from a solar and from a terrestrial magnetic standpoint. Many small bright eruptions occurred on August 6, 7, and 8 (Plate VI*f*) in the huge northern spot group (Greenwich 8181, August 3–16), and on August 9 at $14^h39^m$ G.C.T. (Plate VII*a*, $15^h13^m$), a large eruption occurred in this group when not far east of the central meridian. This was photographed during the sharp magnetic storm registered at Greenwich, August 9, $4^h$, to August 10, $4^h$ G.C.T. Throughout the greater part of this month, however, the number of active spot groups, sometimes showing several eruptions at once, was too great to permit satisfactory comparisons to be made between individual solar outbursts and the numerous magnetic disturbances, including four

of the eight great storms of the year, given in the Greenwich records. If little or no light is thrown by these observations on the length of the time interval, they help to strengthen the evidence in favor of a direct connection between solar eruptions and terrestrial magnetic effects.

Passing over many cases in the Mount Wilson records which indicate a general relationship but uncertain individual correspondence between solar eruptions and terrestrial magnetic storms, we come to an instance of a more definite nature.

### THE ERUPTIONS OF JANUARY 24 AND 25, 1926

As stated in the introductory article of this series, my first crude spectrohelioscope, after some preliminary tests, was set up in Pasadena at my new Solar Laboratory in January, 1926. After a number of experiments with a variety of slit combinations, focal lengths, etc., the apparatus was still in an undeveloped state when a large bright eruptive prominence was detected on January 24 (Plate VII*b*) in and following the largest spot group on the disk, at about 21° north latitude. The details, showing rapid changes in form, were fairly well seen for about twenty minutes after $19^h40^m$ G.C.T., but I was then unfamiliar with the use of the spectrohelioscope in observing complex objects, and was also unable to continue the work that day. During the following morning and part of the afternoon a renewal of this eruption was extremely brilliant; in fact, it was the most remarkable solar phenomenon I have ever seen. The forms of the bright and dark flocculi not only repeatedly changed very materially within a few minutes, but when the oscillating slits were set at different wave-lengths there were extraordinary transformations of structure and brightness. Some of these were of the type described in my last article, showing strong dark hydrogen flocculi descending at high velocities into the two umbrae of the largest spot of the group. I found the $D_1$, $D_2$, and $D_3$ lines (with stationary slits) to be brightly reversed in the large spot, while $D_3$ appeared in regions beyond its boundaries as a dark line, greatly distorted toward the red. Observations of the forms of these helium areas were not very satisfactory, as the multiple slits, then not adjustable in width, were too wide for this line. Nevertheless, some bright and

dark helium flocculi were apparently seen, but no definite structure could be made out with $D_1$ and $D_2$ of sodium or $b_1$ of magnesium. On January 26 the great eruption had ceased, though a very small but brilliant eruption, lasting only a few minutes, was observed on the bridge over the large spot at about $20^h10^m$ G.C.T. This was followed by the appearance of slender dark flocculi, similar to those illustrated in the first paper in this series.

On January 26 the most intense magnetic storm in five years was recorded at Greenwich and elsewhere. This disturbance commenced at $16^h30^m$ G.C.T. (when the largest spot was about 27° west of the central meridian), rose to a considerable maximum, and subsided soon after $5^h$ on the following morning.[1] A brilliant aurora was seen in Norway and North America on the night of January 26. Professor Störmer wrote me as follows from Oslo regarding his observations: "I have been most fascinated by a remarkable aurora here on the 26th January of exceedingly *red* color, like the aurora in 1870. I should like to know from which active part of the sun this aurora was coming."

Unfortunately the exact time interval between the beginning of the solar and the terrestrial disturbances cannot be stated, as it is not certain whether the eruption of January 24 or the much more brilliant one of January 25 was involved.

## THE ERUPTION OF FEBRUARY 22, 1926

On February 22, 1926, Dr. Royds and his assistants at the Kodaikanal Observatory obtained several spectroheliograms of an outburst on the sun's disk surpassing in brightness any contained in the whole of the Kodaikanal record extending from 1904. It occurred near the active spot observed on January 24 and 25, then at 23° north latitude and 9° west of the central meridian, approximately where the eruption described above was observed visually at Pasadena on the previous rotation.

Spectroheliograms were begun at $7^h51^m$ I.S.T. (G.M.T. $+5^h30^m$). Fig. 1 is an enlargement from the first $H\alpha$ spectroheliogram at $8^h3^m$ of a region near the active spot near the center of the figure. The spot's position is 23° N. and 9° W. of the central meridian. Fig. 1 exhibits, in addition to dark markings and the

[1] *Nature*, **117**, 208, 1926.

usual bright flocculi, some parts of the flocculi which are much brighter than the rest, but this is not very exceptional. What is very unusual is to see these brighter parts develop into such intense and extensive bright filaments as exhibited in the later photographs.

By $8^h8^m$, fig. 2, there is considerable growth in length and intensity; at $8^h36^m$, fig. 3 [Plate VII*c*], there is further development, the more westerly branch now actually touching the sunspot, whilst the large dark marking seen to the north in figs. 1 and 2 has disappeared in fig. 3. Since the dark marking is restored, though in modified form and extent, in a spectroheliogram taken at $8^h41^m$ with the slit set on the red edge of the $H\alpha$ line, its apparent disappearance from fig. 3 should probably be attributed to Doppler displacement of the darkened $H\alpha$ line. The dark marking reappears considerably changed in form in the spectroheliogram taken with the slit central on the $H\alpha$ line at $10^h24^m$ and is maintained thereafter.

Fig. 4 [Plate VII*d*] is a calcium $K_{2_3}$ spectroheliogram taken at $9^h0^m$. This spectroheliogram was intentionally under-exposed to prevent the ordinary flocculi from developing into the dense white masses familiar to all who have seen calcium spectroheliograms. In consequence of the under-exposure, the ordinary flocculi appear in only medium brightness, but the relative brilliance of the bright filaments is made clear.

The maximum development in brilliancy of these filaments was reached at $9^h4^m$, shown in fig. 5 [Plate VII*e*]. Subsequently the filaments persist with some changes of form, but become less brilliant. They were still striking in the last spectroheliogram taken at $15^h6^m$.

The bright filaments described were due, of course, to brilliant reversals of the $H\alpha$ and K lines. The reversals in the $H\alpha$ line were examined visually in the spectroscope; the reversal was not, in general, displaced, but the dark $H\alpha$ line was displaced locally by over 2 A. Mr. S. Balasundaram Iyer, Assistant, making visual observations of disc phenomena with another telescope, found that near the umbra of the spot the $D_1$, $D_2$ and *b* lines were also reversed; $D_3$ was dark to the north of the spot.[1]

In his description of the great magnetic storm of February 23–25, 1926, H. W. L. Absalom of the Eskdalemuir Observatory notes that it lasted longer than that of January 26–27, which it followed after an interval of twenty-eight days. The Eskdalemuir records show that the second storm began shortly after $14^h$ on February 23. The maximum ranges in the N and W components of force occurred at approximately $16^h30^m$ on February 24. The absolute maximum in vertical force occurred between $16^h14^m$ and $17^h42^m$, during which interval the spot of light was off the photographic paper. The ranges

[1] Royds, *Monthly Notices of the Royal Astronomical Society*, **86**, 381, 1926.

in *N*, *W*, and *V* during the earlier part of the storm were distinctly less than the ranges in the latter part. In this respect this storm differed from that of January, in which the extreme ranges and most rapid changes occurred during the first thirteen or fourteen hours.[1]

The interval between Dr. Royd's first photograph (February 22, $2^h21^m$ G.M.T.) and the beginning of the magnetic storm (February 23, shortly after $14^h$) was thus about thirty-six hours, while the interval between the maxima of the eruptive and magnetic phenomena was about forty-four and a half hours.

### THE ERUPTION OF OCTOBER 13, 1926

The next exceptional eruption on the disk to which attention may be called here is that photographed by MM. D'Azambuja and Grenat at the Meudon Observatory on October 13, 1926.

A cette date, à $13^h15^m$ (T.U.), une image de la couche supérieure de l'hydrogène ($H\alpha$), obtenue avec le grand spectrohéliographe de Meudon, a révélé la présence d'une masse étendue de gaz d'un éclat tout à fait exceptionnel, dans la région occupée par un des groupes de taches, sur le point de traverser le méridien central.

C'est de beaucoup l'éruption la plus intense qui ait été observée à Meudon où les images de l'hydrogène sont enregistrées d'une manière continue depuis 1909.

Le phénomène paraît avoir été très court. A $11^h5^m$, en effet, une épreuve de la couche supérieure du calcium ($K_3$) n'offrait encore rien de remarquable dans la même région. Une seconde image de l'hydrogène, à $14^h41^m$, ne montrait plus que les parties saillantes de la masse de gaz, très diminuées d'éclat.

A $14^h35^m$, pendant la phase de déclin, la raie $H\alpha$, observée visuellement, semblait peu déviée de sa position normale, même dans les régions les plus brillantes de l'éruption, marquées par des renversements intenses. Mais elle était doublée en plusieurs points, du côté des grandes longueurs d'onde, par une raie sombre assez fine, annonçant la présence de masses hydrogénées descendant, ou redescendant, sur le Soleil avec une grande vitesse, de l'ordre de 130 km/sec. Ces mouvements de descente se révélaient encore, aussi rapides, sur la dernière épreuve du spectro-enregistreur des vitesses, à $15^h37^m$.

L'examen visuel de la raie de l'hélium $D_3$, dans la région perturbée, montrait en divers endroits des renversements fins, peu marqués. En un seul point, à $15^h30^m$, la raie était estompée et fortement déplacée vers le rouge (vitesse radiale: 150 km/sec.).

Les trois autres groupes de taches ont manifesté aussi, vers le même temps, une forte activité. Le 14 octobre, en particulier, deux groupes, à l'Ouest,

[1] Absalom, *Nature*, **117**, 416, 1926.

montraient, sur les images de l'hydrogène, des plages faculaires très intenses. Le plus rapproché du bord révélait même, par l'observation visuelle de $H\alpha$, des mouvements radiaux de même sens et aussi importants que ceux présentés la veille par le groupe voisin du méridien central.

Ces marques d'activité solaire exceptionnelle permettaient de prévoir une perturbation magnétique. Celle-ci s'est produite, en effet, très violente dès le 14 Octobre au soir. Elle a débuté à $20^h$, environ 31 heures après l'éruption décelée par le spectrohéliographe, et s'est poursuivie pendant 36 heures. Son maximum d'intensité a été atteint entre 19 et $23^h$ le 15 Octobre, 48 heures environ après le passage au méridien de la région solaire où s'était montrée l'éruption.[1]

Shortly after the first maximum of the magnetic storm, at $21^h15^m$, a diffuse aurora was detected by M. Baldet at Meudon, where a much more brilliant aurora, comprising about a dozen fan-shaped rays, was observed through clouds two hours later. This aurora was also seen in Germany and America.

As the solar eruption was apparently of short duration, the authors, as stated above, consider the interval between its appearance and the beginning of the magnetic storm to have been about thirty-one hours.

## OTHER SOLAR ERUPTIONS

As the purpose of this paper is chiefly to indicate to observers undertaking work with the spectrohelioscope the characteristic phenomena of certain outstanding eruptions, most of which have been closely followed by magnetic storms, no attempt has been made to enter into an exhaustive examination of all the records. Mention should be given, however, to a few other cases.

One of these was illustrated in a series of lantern slides by Mr. Evershed at a meeting of the Royal Astronomical Society on November 12, 1920. These included

a set of calcium images of the Sun's disc taken on June 30, 1916, showing how an ordinary sun-spot group of no particular interest suddenly becomes the seat of a tremendous disturbance. There is a great evolution of calcium light, superposed apparently upon the flocculi; and it is remarkable that at the same time other brilliant points appear on another spot-group, and at the limb an eruptive prominence was photographed. The very brilliant stage only lasted some 15 minutes, and after it had entirely faded away the flocculi appeared practically unchanged for the rest of that day.[2]

[1] *Comptes rendus*, **183**, 701, 1926.

[2] *Observatory*, **43**, 411, 1920.

According to Newton, who has recently published a list of similar eruptions and magnetic disturbances, no magnetic storm followed this outburst, which was at 12° north latitude and 16° west of the central meridian.[1] Another similar case in Newton's table is an (unpublished) eruption photographed by Evershed at 15° north, 23° west on September 14, 1928, which was followed by only a small magnetic storm after the lapse of four and a half days. At a greater distance from the central meridian (21° S., 44° E.) was the bright hydrogen eruption photographed by Richardson at Mount Wilson on January 23, 1928, followed by a moderate magnetic disturbance between ten and thirty-one hours after its formation.[2] The brilliant flocculi observed by Newton with the Greenwich spectrohelioscope through clouds on August 12, 1930, at 7° south, 3° west occurred during an unsettled magnetic period, and its connection with a small magnetic storm recorded nearly two days later may be a chance coincidence.

The most interesting solar disturbance hitherto observed with the spectrohelioscope at Greenwich is briefly described in a recent number of *Nature* as follows:

> The phenomena observed on Nov. 25 evidently represented the end-on view of an eruptive prominence blown out of the sun's chromosphere with a maximum observed velocity of 450 km./sec. Forty-five minutes before the eruption, an apparently stable dark marking was visible; at $10^h34^m$ G.M.T. the velocity rose within a few minutes from 40 km./sec. to about 400 km./sec. At $11^h$ cloud stopped the observations, but the eruption was then declining, and part of the gaseous structure was descending at about 100 km./sec. Contemporary with the appearance of those rapidly moving masses of hydrogen gas, brilliant patches of hydrogen with little or no radial velocity made their appearance.[3]

Such a sudden and unexpected rise, at high velocity, of an apparently inactive dark flocculus, then near the center of the disk, merits special consideration.

[1] "An Active Region of the Sun on 1930 August 12," *Monthly Notices of the Royal Astronomical Society*, **90**, 824, 1930.

[2] "An Exceptional Sun-Spot," *Publications of the Astronomical Society of the Pacific*, **40**, 126, 1928.

[3] *Op. cit.*, **126**, 969, 1930. A detailed account of this eruption has since appeared in *Monthly Notices of the Royal Astronomical Society*, **91**, 239, 1930.

Excluding all cases in which the initial phase of the solar eruption was not fairly well known, we have the following approximate time intervals between the beginning of the eruptions and the outbreak of intense magnetic storms:

| Solar Eruption | Time Interval (Hours) |
|---|---|
| September 1, 1859 | 17.5* |
| July 15, 1892 | 19.5† |
| September 10, 1908 | 26 |
| February 22, 1926 | 36 |
| October 13, 1926 | 31+ |
| | 26 |

* This interval might have been greater if Carrington had observed with calcium or hydrogen light.

† The violent series of deflections did not begin until five hours later.

The mean value of about twenty-six hours, which is probably not very greatly in error, may be compared with Maunder's mean time interval of twenty-six hours between the central meridian passage of large active sun-spots and the beginning of the subsequent magnetic storms.

## THEORIES OF THE AURORA

A very brief reference to theories of the aurora will suffice for the purposes of this paper. The early history of the corpuscular theory has been given by Carl Störmer,[1] whose interesting account is partially outlined here.

E. Goldstein suggested in 1881 that the sun emits electrical rays (subsequently considered to be cathode rays), and thus sought to explain the mysterious connection between variations in solar activity and terrestrial magnetism. In 1894 A. Paulsen attributed the aurora to cathode rays, which he supposed to originate in the upper strata of the earth's atmosphere. Two years later K. Birkeland found that a magnetic pole, acting like a lens on parallel light, caused a beam of cathode rays to condense toward a point. He therefore ascribed the aurora to such an effect of the earth's magnetic field on cathode rays coming from the sun. By experimental tests with a spherical electromagnet exposed to a stream of cathode rays, he was able to imitate the principal phenomena of the aurora. S. Arrhenius, in 1900, attributed the repulsion from the sun of electrified particles causing the aurora to the effect of radiation pres-

[1] *Journal of Terrestrial Magnetism*, **22**, 23, 97, 1917.

sure. As E. Pringsheim and R. J. Strutt have shown, the repulsive force cannot be due to thermal convection.[1] Nor can it be electrical, because it acts upon neutral as well as ionized atoms.[2]

Störmer's extensive researches were begun in 1903. Starting from the mathematical investigations of H. Poincaré, and assuming the motions of the earth and sun to be negligible, the earth's field to be that of a uniformly magnetized sphere, and all terrestrial forces other than the earth's magnetism to be absent, he calculated the trajectories of electric corpuscles coming from the sun. The results were so satisfactory that he has since continued his investigations with great activity and success, and tested them by extensive visual and photographic observations in high latitudes. In his later work he has enlarged the range of his researches, and has studied the trajectories of both positively and negatively charged particles moving at various velocities. In this way he has been able to account for the latitude of the zones of maximum auroral frequency and to explain why auroras extending into comparatively low latitudes are always accompanied by magnetic storms.

It is evidently a matter of importance to determine the source, nature, and velocities of the solar particles assumed by this theory and others to be the cause of auroras. The suggestion that high speed $\beta$ or $\alpha$ particles are emitted by radioactive phenomena was opposed by F. Lindemann, on the ground that they would require incredible radioactivity in the sun, that charged particles having the same sign could not remain together in transit because of electrostatic repulsion, and for other reasons. He therefore attributed magnetic storms to recombination in the upper atmosphere of electrons and ions ejected as ionized clouds of neutral charge from the sun in eruptive prominences and propelled by light-pressure.

The effect of radiation pressure on gaseous particles in solar and stellar atmospheres has also been studied by Saha, Milne, Johnson, Sur, Chapman, S. R. Pike, and others. Milne's paper "On the Possibility of the Emission of High-speed Atoms from the Sun and Stars"[3]

[1] Pringsheim, *Physik der Sonne*, p. 225, 1910; Strutt, *Monthly Notices of the Royal Astronomical Society*, **57**, 59, 1916.

[2] Sur, *Astrophysical Journal*, **63**, 111, 1926.

[3] *Monthly Notices of the Royal Astronomical Society*, **86**, 459, 1926.

is of special importance in its bearing on solar eruptions of the type described in the present article. His principal conclusions in this connection are as follows:

1. An atom which, due to some cause or other, begins to move outward from the sun with an appreciable velocity will begin to absorb in the violet wing of the absorption line corresponding to the same atom at rest, owing to the Doppler effect. It will therefore be exposed to more intense radiation. If it was originally a high-level atom in equilibrium under radiation-pressure and gravity, radiation-pressure will now exceed gravity, and the atom will be accelerated outwards. It will therefore move still further out into the wing, where it will be exposed to still more intense radiation, and so on, until it eventually "climbs out of" its absorption line and becomes exposed to the undiminished continuous spectrum.

2. The atom will ultimately acquire a limiting velocity, in virtue of the weakening of the radiation under the inverse square law. A limiting velocity may also be acquired in virtue of the atom being "trapped" by an adjacent absorption line.

3. For atoms projected from the sun in this way, from absorption lines of an intensity ratio of the order of 1/9, the limiting velocity is of the order of $1.6\times10^{8}$ cms. sec.$^{-1}$ (1600 kms. sec.$^{-1}$). The velocity will be about the same for light atoms (e.g. *H*, *He*) and for heavy atoms (e.g. $Ca^{+}$).

. . . . . .

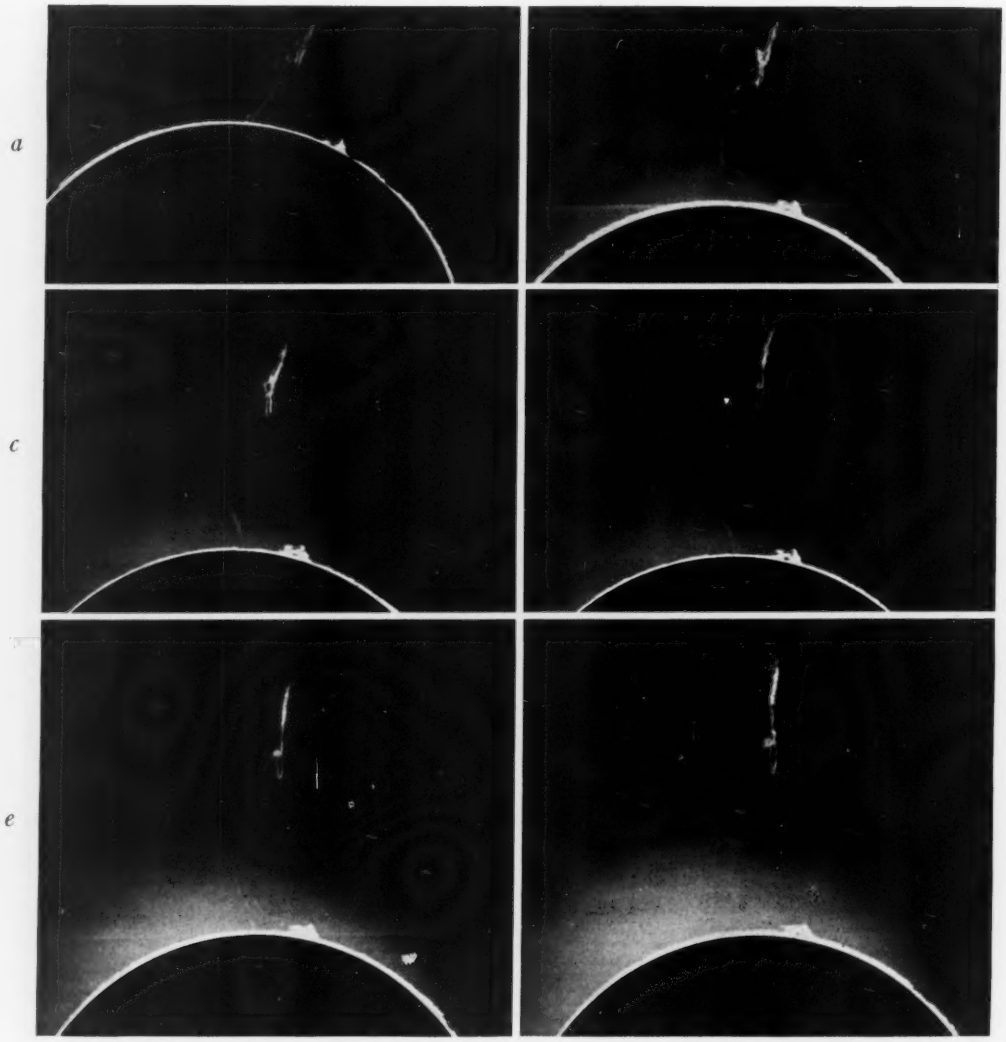
6. Particles projected in this way from the sun may be the cause of aurorae and magnetic storms. Comparison is made with Lindemann's theory. On the present theory the particles arrive with greater velocities, and may be much heavier, than on Lindemann's theory.

7. Use is made of Blackett's observations of the collisions of $\alpha$-particles with argon atoms to estimate the air-range of $Ca^{+}$ atoms (same atomic weight as argon) moving at $1.6\times10^{8}$ cms. sec.$^{-1}$. The equivalent air-range at N.T.P. is about 0.15 cm., which would be just about sufficient for them to penetrate the earth's atmosphere to the 100 kms. level, the observed lower level of aurorae.

8. Atoms may be projected neutral or ionised. Neutral atoms may become ionised and form neutral clouds, as in Lindemann's theory. Ionised (positively charged) atoms will be followed by an equal number of electrons, but the electrons will not be subject to appreciable radiation-pressure and will probably lag behind. Hence the cloud (if the projected particles are numerous enough to form such) will have a positively charged head and a negatively charged tail.

9. The phenomenon of accelerated escape will only occur if the atoms are not numerous enough to give rise to an absorption sufficient to "carry their absorption line with them." Random accelerated escape is possible at any time from any portion of the sun's surface, but escape is more probable from disturbed areas.

## PLATE VIII




Eruptive prominence photographed at Kodaikanal November 19, 1928: *a*, $7^h52^m$; *b*, $8^h35^m$; *c*, $8^h45^m$; *d*, $8^h52^m$; *e*, $8^h58^m$; *f*, $9^h3^m$, I.S.T. Outward velocity 60 to 70 km/sec. in lower parts of prominence, 100 to 170 km/sec. in highest parts. Velocity increased with time, reaching 229 km/sec. at top between *e* and *f*. Height in *f* 495,000 miles; cut off by clouds at maximum height of 567,000 miles.

Pike's valuable contributions to the subject, so sadly terminated by his early death, will be discussed in a later paper of this series on the motions of hydrogen near sun-spots. In the present connection his most important conclusion is that "the vertical instability, due to the Doppler effect, which was first pointed out by Milne, is found to have a horizontal counterpart. An atom moving upwards is accelerated horizontally, resulting in a rapid dispersal of upward-moving clouds."[1] This seems to be borne out by the eventual diffusion of many eruptive prominences, though there are occasional exceptions of the type represented by Royds's remarkable series of photographs reproduced in Plate VIII.[2] As Pike stated, a difficulty of the radiation-pressure theory is to account for the extremely rapid acceleration of quiescent dark flocculi which suddenly shoot upward at great velocity. A very striking case of this kind is that recently described by Newton (see p. 401).

S. Chapman, who has made extensive investigations on the passage of charged particles from the sun to the earth and the motion of a neutral ionized stream in the earth's magnetic field, believes some form of corpuscular theory to be promising, but considers that the difficulties of the problem have been only partly overcome. In a recent paper he has discussed the theory of Hulburt and Maris, which ascribes auroras and magnetic storms to the action of small temporary spots of very high temperature on the sun, from which blasts of ultra-violet light ionize the gases at high levels in the earth's atmosphere. The ions thus formed descend in spirals around the lines of force toward the northern or southern auroral zones.[3] Chapman maintains that these terrestrial corpuscles, with a speed of about 10 km/sec., could not possibly penetrate the atmosphere to the observed lower level of the aurora.[4] It may be added that the existence of these supposed intensely hot regions has not yet been demonstrated. They are not shown in Pettit's photographs of the sun made with ultra-violet light, where they presumably ought to

[1] "The Motion of Gases in the Sun's Atmosphere," *ibid.*, **88**, 3, 1927.

[2] "A Very High Prominence on 1928, November 19," *ibid.*, **89**, 255, 1929.

[3] Hulburt, *Physical Review*, **34**, 1167, 1929.

[4] "On Solar Ultra-Violet Radiation as the Cause of Aurorae and Magnetic Storms," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, **2**, 296, 1930.

appear, or by spectroscopic means, though Carrington's observations might perhaps have been a case of this kind.[1]

Deslandres, who has published a number of papers in the *Comptes rendus* on the relationship between solar and terrestrial magnetic phenomena, summarizes his opinion regarding the source and nature of the charged particles as follows:

> Tout se passe comme si le Soleil avait sous la surface une couche profonde qui tourne comme un corps solide; et cette couche quasi solide offre 24 volcans, variables comme les volcans terrestres, et uniformément répartis autour de l'axe de rotation, qui rejettent au dehors la matière électrisée des masses intérieures. Si l'on admet que les particules négatives ou positives de ces volcans ont des vitesses différentes et sont lancées surtout par des corps radioactifs, on explique bien les particularités de nos orages. De plus, le rayonnement corpusculaire de la couche profonde apparait comme la cause première de tous les phénomènes (taches, facules, polarités magnétiques, etc.) observés sur le Soleil et ses dépendances.[2]

From an exhaustive discussion of the magnetic records covering the period 1906–1925, inclusive, Chree and Stagg arrived at the following conclusions:

> The 27-day interval has been found to present itself in disturbance of any size, large or small. No certain difference has been found in the length of the interval, as between years of low and years of high sunspot latitude, or as between years of many and years of few sunspots. No certain departure has been found from 27.0 days in any type of years. There is an apparent tendency for the interval to be greater the larger the primary disturbance. But this is, at least partly, due to the tendency in very large disturbance to rise more quickly than it falls.
>
> The secondary pulse following 27 days after large disturbance is due, in part, to an increase in the proportion of highly disturbed days, but it also owes a good deal to a diminution in the proportion of very quiet days. Similarly, the secondary pulse following 27 days after exceptional magnetic quietness is due, in part, to an increase in the proportion of very quiet days, but it also owes a good deal to the diminution in the proportion of very disturbed days.
>
> The secondary pulse is better developed in years of few than in years of

[1] It seems very probable that any such ultra-violet outbursts, if they exist, will coincide in time and position with the calcium and hydrogen eruptions described in this paper. If so, the observed time interval between the solar and terrestrial effects should serve as another means of testing the theory of Hulburt and Maris.

[2] For a more complete statement of M. Deslandres' views see his paper entitled "Loi de distribution des orages magnétiques et de leurs éléments. Conséquences à en tirer sur la constitution du Soleil," *Comptes rendus*, **185**, 626, 1927.

many sunspots, and better in years of low than in years of high spot latitude, but other causes helping or hindering its development seem to exist.

In some years there seems a decided tendency for the international quiet and disturbed days to form members of the same sequence. Supposing magnetic disturbance due to radiation of some kind from the sun, and the solar area effective on any one day to be a narrow zone, then some solar zones must retain their disturbed condition for many solar rotations, whilst others must be alternately much more disturbed than the average zone and much less.

No trace has been found of the existence of any disturbance interval which is a submultiple of 27 days, but there seems in all kinds of years a decided tendency for high disturbance to develop from 4 to 6 days after the occurrence of conspicuous quietness.[1]

Greaves and Newton, who have since discussed this problem in a paper entitled "Large Magnetic Storms and Large Sunspots,"[2] reach the following conclusions:

A comparison between the large magnetic storms and large sunspots during the period 1874 to 1927 shows that individual storms and individual spots are associated with each other more often than can be ascribed to mere chance. The tendency to association appears to be greater for the very largest storms of all. It would seem that whatever solar activity is responsible for a magnetic storm, if it is sufficient to produce an unusually large storm, it will probably manifest itself as a large sunspot. But attention has been called to a case of a very large storm taking place at a time when only very moderate spots were visible.

No very definite evidence has been found of a tendency for these large storms to be followed by another magnetic disturbance after an interval of one solar rotation. The evidence available suggests that there may be a slight tendency for recurrence, but it is not very conclusive.

In a later paper they state:

It would thus appear that the recurrence characteristic is mainly a property of the storms of smaller range. The recurrence tendency has been used to ascribe magnetic storms to the action of radial streams proceeding from limited areas of the sun. The present investigation in no way contradicts this conclusion, but suggests an additional hypothesis, namely, that for the more intense storms the solar disturbance from which the stream is being ejected is in general short-lived, and does not survive a solar rotation in an appreciable number of cases.[3]

After giving the average areas of the largest sun-spots at the time of commencement of magnetic storms, they add:

[1] "Recurrence Phenomena in Terrestrial Magnetism," *Philosophical Transactions of the Royal Society of London*, A, **227**, 61, 1927.

[2] *Monthly Notices of the Royal Astronomical Society*, **88**, 567, 1928.

[3] *Ibid.*, **89**, 641, 1929.

On comparing the data in this table with the diagram, there is seen to be a marked antithesis between the tendency to recurrence and the tendency for the storms to be associated with spots. The paradox, however, is more apparent than real, as the occurrence of storms during spotless periods shows that the spots themselves are not the actual seat of origin of the streams responsible for the storms. All that can be said is that there is a tendency for the solar disturbances responsible for the larger storms to be accompanied by spots larger than the average, and once it has been granted that the disturbances are not identical with the spots, there seems to be no serious difficulty in assuming that the larger disturbances may subside comparatively quickly although an associated spot may persist. In one respect the two sets of data are supplementary, as they both seem to indicate that the storms are connected with a disturbance on a limited area of the sun's surface, the recurrence tendency suggesting this for the smaller storms, whereas the correlation with sunspot data points to the same conclusion in the case of the larger storms.

In considering the foregoing theories the following results of my observations may be of service:

1. Quiescent prominences observed or photographed with *Hα* on the sun's disk as dark flocculi commonly lie upon a brighter background of hydrogen, which often appears as a narrow frame partially surrounding the absorbing gas. Good illustrations of this effect may be seen, for example, in several of the spectroheliograms reproduced in the first paper of this series.[1]

2. The brighter eruptive flocculi, which develop suddenly, often as brilliant points, are frequently capped in a few minutes by dark hydrogen, changing rapidly in form. As Newton has remarked, these bright flocculi produce, in general, only a small displacement of the bright *Hα* line, corresponding to a velocity of ascent of a few kilometers per second. The velocity of the absorbing gas usually exceeds that of the bright flocculi from which it appears to rise.

3. As shown in the second article of this series, the absorbing hydrogen, after a rapid ascent, may often be seen rapidly falling toward a sun-spot or even toward the photosphere away from a spot. The failure of the gas to escape from the sun may result from one or more causes, including the influence of the spot, the angle of dis-

[1] "The Spectrohelioscope and Its Work," Part I, Plates XXI, XXII, XXIII, *Mt. Wilson Contr.*, No. 388; *Astrophysical Journal*, **70**, 265, 1929. See also "Visual Observations of the Solar Atmosphere," *Mt. Wilson Communication*, No. 97; *Proceedings of the National Academy of Sciences*, **12**, 224, 1926.

charge, and the tendency of the absorbing atoms when too numerous to "carry their absorption line with them."

Bright eruptions, due to increased radiation from lower levels, seem to offer the most promising means of escape from the sun. The observed acceleration of the radial velocity, if confirmed at the sun's limb by the accelerated rise of prominences, is in harmony with the demands of the radiation-pressure theory of Milne. The high velocities needed to escape completely from the sun may be attained at higher levels, where the gas is too faint to be visible.

Whatever the underlying cause of the eruptions, they are almost sure to be shown in their early stages by the spectrohelioscope, either as bright flocculi or as superposed dark flocculi moving at accelerated velocities.

## INTERNATIONAL CO-OPERATION IN WORK WITH THE SPECTROHELIOSCOPE

If we could take the observations given in this paper at their face value, supported as they seem to be by theory, we might conclude that bright auroras and exceptional magnetic storms result from solar eruptions, which carry charged particles to the earth in periods ranging from about eighteen to thirty-eight hours. It must be remembered, however, that the actual beginning of very few such eruptions has been observed, so that the true time intervals are still very uncertain. Moreover, in some cases the terrestrial magnetic storms commenced before these particular eruptions were recorded, though other outbursts may have preceded them. We must also bear in mind that several eruptions have occurred near the center of the sun without producing magnetic storms and that many magnetic storms without known solar antecedents have been registered, even at periods of minimum sun-spot activity.

It is probable that some of these discrepancies are due to the angle at which the eruptive gases left the sun and the form of their subsequent trajectories, not to speak of their possible diffusion after the manner described by Pike. But satisfactory conclusions will be possible only when more continuous solar observations become available.

Anyone who has regularly watched the sun with a spectrohelio-

scope is aware how suddenly and unexpectedly a bright or dark eruption may appear on the disk. My own observations include scores of such eruptions, most of which were relatively small. Moreover, as already remarked, a dark flocculus which has remained almost unchanged for days may instantly quicken into life and move rapidly horizontally or vertically, or completely disappear within a few minutes. Any of these phenomena, though far more common near or within a large group of sun-spots, may also happen at other points on the disk. It is therefore obvious that our observational means have been very inadequate in the past, though much could be accomplished with existing spectroheliographs if it were feasible to take *Hα* photographs at half-hour or shorter intervals throughout the day. Even then, the small number of active spectroheliographs, their irregular distribution in longitude, and the interruptions due to cloudy weather would render the total record incomplete, especially when contrasted with the continuous photographic registration of the three elements of terrestrial magnetism at many stations.

The suitability of the spectrohelioscope for the required observations and the possibility of constructing a complete and efficient outfit at small expense offer the best available means of keeping the solar atmosphere almost continuously under view. I am glad to say that twenty-five coelostat telescopes and spectrohelioscopes of the type described in the first article of this series have already been built or ordered for use at widely distributed stations, most of which are listed in Table I.

Two other spectrohelioscopes of the standard type, which have just been completed, will be erected at favorable sites, and several others are likely to be built for use elsewhere. A general scheme of co-operation for the detection of eruptions on the sun's disk, in which spectroheliographs may also take part, will be organized in harmony with the present co-operative work of the International Astronomical Union.

A simple device for transforming a spectrohelioscope into a spectroheliograph, which has been built and tested at my Solar Laboratory, will be described in a later article of the present series. I have also designed a very inexpensive spectroheliograph, which

can be employed as a useful auxiliary of the standard spectrohelioscope, especially when it is desired to photograph quickly the forms of rapidly changing eruptive phenomena. In slightly modified form this spectroheliograph can be used as an automatic recorder, giving calcium images of the sun at any desired time intervals throughout the day.

TABLE I

SPECTROHELIOSCOPES

| Observatory | Place | Latitude | Longitude |
|---|---|---|---|
| Royal | Greenwich, England | +51°29′ | $0^h\ 0^m$ |
| Solar Physics | Cambridge, England | +52 13 | 0 0 |
| Federal | Zürich, Switzerland | +47 23 | − 0 34 |
| Astrophysical | Florence, Italy | +43 45 | − 0 45 |
| American College | Beirut, Syria | +33 54 | − 2 22 |
| Solar Physics | Kodaikanal, South India | +10 14 | − 5 10 |
| Department of Terrestrial Magnetism of the Carnegie Institution of Washington | Watherhoo, Australia | −30 18 | − 7 44 |
| National Institute of Astronomy | Nanking, China | +32 7 | − 7 55 |
| Commonwealth Solar Observatory | Canberra, Australia | −35 20 | − 9 56 |
| Dominion | Wellington, New Zealand | −41 17 | −11 39 |
| Apia | Apia, Samoa | −13 48 | +11 27 |
| Mount Wilson, Carnegie Institution of Washington | Mount Wilson, Calif. | +34 13 | + 7 52 |
| Mount Wilson, Carnegie Institution of Washington | Pasadena, Calif. | +34 8 | + 7 52 |
| Pomona College | Claremont, Calif. | +34 6 | + 7 51 |
| University of South Dakota | Vermilion, S.D. | +42 42 | + 6 28 |
| Yerkes | Williams Bay, Wis. | +42 34 | + 5 54 |
| Adler Planetarium | Chicago, Ill. | +41 50 | + 5 51 |
| Ohio State University | Columbus, Ohio | +40 0 | + 5 32 |
| Department of Terrestrial Magnetism of the Carnegie Institution of Washington | Huancayo, Peru | −12 3 | + 5 1 |
| Vassar College (Physical Laboratory) | Poughkeepsie, N.Y. | +41 41 | + 4 56 |
| Bell Telephone Laboratories | New York City, N.Y.* | +40 45 | + 4 56 |
| Massachusetts Institute of Technology (Physical Laboratory) | Cambridge, Mass. | +42 23 | + 4 44 |
| Franklin Institute | Philadelphia, Pa. | +39 58 | + 5 1 |

* This instrument will probably be erected at a site several miles from the Bell Telephone Laboratories in New York City.

This paper may appropriately close with a suggestion regarding the desirability of retaining an open mind toward the many theories under consideration. No one who has devoted years of observation to the complex phenomena of the solar atmosphere is likely to underrate the difficulty of the problem. Radiation pressure as presented by Milne seems to account for the support of $Ca^+$ vapor in the solar

atmosphere and its escape from the sun if the ionized atom is being accelerated, but the difficulties are greater with hydrogen, which in prominences reaches nearly to the height of calcium, though there are some differences in distribution. Moreover, Pettit, who made an extensive study of the subject at the Yerkes Observatory, does not believe that the gases in eruptive prominences rise with a constant acceleration. It is evident that much observational work, both visual and photographic, remains to be done in this field.

Many of the phenomena observed on the sun's disk with the spectrohelioscope are also very puzzling. In the radiation-pressure theory a sun-spot should be a center of attraction for neighboring ascending gases, but its influence on those at great distances should be negligible, as Pike has pointed out. Dark arches of hydrogen, it is true, usually rise from bright hydrogen flocculi, but they also frequently descend at high velocity upon or toward bright flocculi or upon apparently normal regions of the photosphere away from spots. It is desirable, as Pike has suggested, to determine by searching for local magnetic fields whether invisible whirls exist at these apparent points of attraction. Such questions, with others to be mentioned in subsequent papers, will provide ample occupation for anyone equipped with the necessary instruments.

I wish to express my thanks to Messrs. Fox and Abetti, Ellerman, Nicholson, Royds, and D'Azambuja, whose photographs of eruptive phenomena are reproduced in this paper. My indebtedness to others who have supplied information has already been acknowledged in the text.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
March 1931

## ALBERT A. MICHELSON

The editors of the *Astrophysical Journal* announce with deep regret the death of Professor Albert A. Michelson at Pasadena, California, on May 9, 1931. Professor Michelson had been a collaborating editor of the *Journal* since its foundation in 1895. He and his associates had just completed the installation and preliminary readings for a new determination of the velocity of light in vacuo. A report on the results of this experiment and a sketch of the life of Professor Michelson will appear in a later number of this *Journal*.

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*and*

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Photographs taken by Professor Ross with his new doublet of high speed and wide angle:

N8. Orion and its nebulosities. Exposure time, 5 hours. See the *Astrophysical Journal* for April, 1927.

MW22. The Milky Way in Monoceros, showing bright and dark nebulae. Exposure, 8 hours.

N81. A region in Taurus showing the Pleiades, dark nebulae, and the nebula N.G.C. 1409.

N83. The exterior nebulosities of the Pleiades. Exposure, 10 hours.

Other interesting regions taken with this remarkable lens will soon be ready. Double slides are in preparation, showing a field taken with photovisual and photographic twin lenses. These indicate, by their contrast, the stars of high color.

Planetary photographs taken by Professor Ross with the 60-inch reflector at Mount Wilson:

P70. Venus, photographed in ultra-violet light, June 6, 24, and 26, 1927.

P71. Venus, 50 ultra-violet photographs on one slide, taken with the 60-inch and 100-inch reflectors, June 5 to July 27, 1927.

P72. Venus. An enlargement of the best exposure photographed on June 6, 1927, with ultra-violet light.

P37. Mars, made in the light of five different wave-lengths, from infra-red to ultra-violet. See the *Astrophysical Journal* for November, 1926.

P67. Mars. A comparison of the ultra-violet and the infra-red images of the foregoing.

P80. Jupiter, made in ultra-violet light, August 20, 1927.

Other photographs:

The Sun:

S18. The sun, showing unusual activity in both flocculi and prominences. A combination of calcium spectroheliograms of different dates (S6 and S90).

S19. The disk with many large spots, October 13, 1926.

S20. Enlargement of large spot of June 30, 1928.

S80. Enlargement of large spot group of September 21, 1926.

S81. Violent eruption of July 17, 1928, projected against disk.

S82. Enlarged view of violent eruption of July 17, 1928.

S84. Development of two brilliant eruptions as projected on the solar disk. July 17, 1928. Six exposures.

S85. Subsidence of second brilliant eruption on solar disk. July 17, 1928. Four exposures.

S86. Spectroheliogram of solar disk, May 2, 1928, showing well-marked double band of spots and flocculi.

S87. Dark calcium flocculus, July 17, 1928.

S150. Massive prominence ("The Bat"), June 7, 1928. Height 36,000 miles.

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